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EFFECTS OF SIMULATED SURFACE EFFECT SHIP MOTIONS ON CREW HABITABILITY. PHASE II.

VOLUME 1. SUMMARY REPORT AND COMMENTS.

(9) Technical rept. Jul 75 - May 79,

(10) W. L. Malone

COMMANDER, NAVAL SEA SYSTEMS COMMAND
(PMS-304)

Department of the Navy
P.O. Box 34401, Bethesda, MD 20084

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Surface effect ships
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Performance effects of motion
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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

From July through September 1975, a series of ship motion simulation experiments was conducted using the ONR Motion Generator at Human Factors Research, Inc., Goleta, CA. These experiments (designated Phase II) were part of a program sponsored by the Surface Effect Ship Project to establish the effects of SES motions on the health and performance of crew members. The motions generated by the simulator were based on the response predicted for a particular 2000-ton SES design, encountering bow seas of states 3, 4 and 5, at speeds of 80, 60 and 40 knots, respectively. Nineteen U.S. Navy enlisted volunteers, who had not had sea-duty experience, were exposed to these motion conditions for periods up to 48 hours in a closed cabin mounted on the motion generator. Performance tasks representative of shipboard activities were administered on a prescheduled basis and scores were recorded. Data on the physiological response of the subjects were obtained. Test data are presented on task performance, cognitive visual functions, physiological stress, sleep, and kinetosis (motion sickness). Motion sickness became the predominant factor in these tests, (over)

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18. SUPPLEMENTARY NOTES (continued)

ship motion on crew health and performance. Other organizations preparing the companion volumes are Systems Technology, Inc., Human Factors Research, Inc., and Naval Aerospace Medical Research Laboratory Detachment.

20. ABSTRACT (continued)

particularly for the sea state 4 and 5 conditions simulated. This volume summarizes these results and comments on their findings.

PMS-304

TR 1070

APRIL 1981

EFFECTS OF SIMULATED SURFACE EFFECT SHIP MOTIONS ON CREW HABITABILITY—PHASE II

VOLUME 1
SUMMARY REPORT AND COMMENTS

COMMANDER, NAVAL SEA SYSTEMS COMMAND
(PMS-304)

Department of the Navy
P.O. Box 34401, Bethesda, MD 20084

PREFACE

From July through September 1975, a series of motion simulation experiments was conducted using the Office of Naval Research motion generator, located at the facilities of Human Factors Research, Inc., Goleta, CA. These experiments (designated as Phase II) were part of a program sponsored by the Surface Effect Ship Project (PMS-304), Naval Sea Systems Command, to investigate the potential effects of surface effect ship motion on the health and performance of crew members. Assisting PMS-304 in this program were the following U. S. Navy agencies and private corporations:

Naval Aerospace Medical Research Laboratory Detachment (NAMRLD)

David Taylor Naval Ship Research and Development Center (NSRDC)

Human Factors Research, Incorporated (HFR)

Systems Technology, Incorporated (STI)

The results of the Phase II test program are reported in a five-volume series, of which this volume, Summary Report and Comments, provides an overview of the program. The other four volumes were prepared independently by authors from the above organizations.

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FIGURES (CONT'D)

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NOMENCLATURE

g_z	Acceleration in the vertical (heave) direction.
σ_{g_z}	Standard deviation of acceleration in the heave direction, g rms.
MSI	Motion sickness incidence. See formulation in Appendix A and Volume III.
σ_{MSI}	Heave acceleration weighted by kinetosis function, g rms. See Appendix A and Volume III.
f_o^+	Characteristic frequency of upward zero crossings of heave acceleration time series.

SUMMARY

From July through September 1975, a series of ship motion simulations was conducted using the Office of Naval Research motion generator, located at the facilities of Human Factors Research, Inc., Goleta, CA. This was the final test sequence in a group of motion simulations that were sponsored by the Surface Effect Ship Project in order to gain first-hand familiarity with SES-like motions and to judge their effect on the performance and habitability of potential crew members. This objective was accomplished, and rough guidelines have been drawn to define SES motion spectra that are acceptable as well as those that are clearly unacceptable.

In these tests the motion generator simulated the heave, roll and pitch motions of a generic 2000-ton SES without an active ride control system. The motions were those that had been developed using a computer mathematical model of the SES and ocean waves. The simulations were for bow seas at states 3, 4 and 5, and SES speeds of 80, 60 and 40 knots, respectively.

Pairs of U.S. Navy enlisted volunteers, who had not had sea duty experience, were subjected to these motions for periods up to 48 hours in a closed cabin mounted on a motion generator. Performance tasks representative of shipboard activities were administered to the subjects on a scheduled basis and test data on the subject's task performance, cognitive visual functions, physiological stress, sleep patterns and motion sickness were obtained. Generally speaking, motor skills started to deteriorate with the onset of motion, and mechanical interference continued to increase with increasing motion level; however, with few exceptions the degradation of performance due to mechanical interference was not judged to be significant for the range of motions tested. Motion sickness was a predominant factor in these tests of inexperienced subjects, particularly in higher sea states. During the time that subjects experienced motion sickness, task performance in general ceased as subjects became unable or unwilling to continue their assignments. Conversely, when motion sickness was not a factor (i.e., at lower acceleration levels), the subjects were able to function with reasonable proficiency.

Based on these findings, it is recommended that the design and operational use of the SES should attempt to limit local heave accelerations to specific habitable levels. For motions with <u>temporal and spectral acceleration levels similar to those simulated</u> in the Goleta

trials, it is recommended that local heave acceleration levels should be limited to 0.1 to 0.15 g rms primarily to avoid motion sickness. If heave acceleration levels persist above 0.2 g rms with similar spectra, it is expected that motion sickness will affect a significant fraction of the crew.

These are broad guidelines based on the complex nature of the spectra simulated and the particular selection of test subjects. Further work is required to be more definitive or to extend the results to more general cases.

INTRODUCTION

The simulations described herein were part of a series of tests whose purpose was to gain familiarity with the effects of Surface Effect Ship (SES) motions. The simulations to date included a set of simulations at the NASA Marshall Space Flight Center (MSFC), and three sets of simulations denoted Phase I, Phase IA, and Phase II at Goleta, California. The last simulation, Phase II, was concerned in particular with the motions of large SES traveling at high speed in rough water and their effect on ship habitability and crew performance. The general approach in all simulations has been to place a test group of Navy enlisted men in a carefully controlled motion environment derived either from predicted SES motions or from measured ship data.

In a preliminary study (1973), nine SES crewmen from the Surface Effect Test Facility (SESTF) at Patuxent River Naval Air Station were tested in a motion generator at the NASA MSFC to observe the effects of the high frequency (0.6 to 5 Hz) components of SES motions and to identify the relative impact of those motions associated with each particular element of the six degrees-of-freedom (6 DOF) simulated there. Five of the nine subjects had experience aboard 100-ton SES craft. The results of those simulations indicated minimal impact, for those motions simulated, and further indicated that future simulations could be limited to 3 DOF because of the predominance of heave, pitch and roll in the SES motions. Hence, subsequent tests were conducted on the Office of Naval Research (ONR) 3 DOF motion generator which at that time was located at the Human Factors Research, Incorporated (HFR) facility at Goleta, California.

In Phase I at Goleta, four of the crewmen from the MSFC simulation were tested for periods of one-half to four hours in motion conditions derived from a 6 DOF mathematical model. That model predicted the motions of a generic 2000-ton SES operating in a starboard bow sea, at sea states 3, 4, and 5, with speeds of 80, 60, and 40 kt, respectively. The derived SES motions, as simulated, did not include the effects of an active ride control system (RCS) and were thus intended to represent the worst-case motion conditions to be encountered within the operating envelope of a 2000-ton SES. (The relationship of these motions to those of the proposed 3000-ton SES, including the attenuating effects of a RCS, will be discussed in a later report.) The Phase I simulation did not reproduce the above motions with 100 percent fidelity; however, the quality of the simulation was judged acceptable for initial tests.

When the crewmen were found able to tolerate the conditions simulated in Phase I, they were tested further (during Phase IA) for 36 to 48 hours under the SS3/80 kt condition and then either the SS4/60 kt condition or an attenuated SS5/40 kt condition. The latter was instituted to simulate ride control effects.

The SESTF crewmen adapted gradually to the motion environment in those tests, managing normal life-support functions such as eating, moving about, and sleeping, and performing tasks such as navigation plotting, cryptography, auditory vigilance, lock opening, keyboard operations, tracking, and equipment maintenance and repair. Although there was some evidence of general muscle and eye fatigue, performance showed no pronounced drop-offs with time over even the maximum periods studied; nevertheless, further testing was indicated because of two main shortcomings of Phases I and IA:

1. The small sample of well-motivated crewmen limited generalization of results to a wider population, and

2. The existing ONR/HFR Motion Generator (MoGen) could not adequately produce the higher acceleration and velocity portions of the commanded motion with the larger Phase IA cab installed. (The Phase IA cab had eating, sleeping and lavatory facilities required by the crew for long test runs.)

Phase II was planned to overcome these deficiencies. The primary objective of the simulation was again to increase and improve the available data base on the effect of 2000-ton SES motions on the performance and health of humans. A secondary objective was to improve the understanding of the relationships between particular characteristics of the predicted environment and the observed or measured effects on volunteer subjects. To meet these objectives, the motion generator system underwent modifications prior to the beginning of the Phase II tests, and a larger number (19) of volunteer subjects without prior shipboard experience were used in the tests.

The principal results of the tests are summarized in this Volume. For additional details, including conclusions and recommendations of the individual authors, the reader is referred to the four main volumes of this report, as follows:

Volume 2 - Facility, Test Conditions, and Schedules (Systems Technology, Incorporated)

Volume 3 - Visual-Motor Tasks and Subjective Evaluations (Systems Technology, Incorporated)

Volume 4 - Crew Cognitive Functions, Physiological Stress, and and Sleep (Human Factors Research, Incorporated)

Volume 5 - Clinical Medical Effects on Volunteers (Naval Aerospace Medical Research Laboratory Detachment)

EXPERIMENTAL FACILITY

The availability of a suitable motion generator for simulation of SES motions was a major limitation of the program. As will become evident, the ONR/HFR MoGen had the best capability for simulating the pitch, heave and roll of the SES at the time of the simulations, and proved adequate for test purposes after the system was upgraded. The experimental facility used in Phase II comprised:

- The up-graded ONR/HFR Ship Motion Generator (MoGen).
- Two almost-identical cabins for the subjects: one mounted on the MoGen; the other stationary.
- A Control Room containing motion control and test apparatus.

Figure 1 is a functional schematic of the MoGen, and Table I lists its performance characteristics. The interior arrangement common to both the static and the moving cabin is depicted in Figure 2. Layout of the Control Room for the tests is shown in Figure 3.

A simplified block diagram showing the various alternative inputs to, and outputs from, the MoGen during Phase II is given in Figure 4. Solid lines depict the main signal flow, while the dotted lines and circles identify recorded outputs. The primary input device was the "NSRDC disc," a digital-to-analog system on which detailed calculated motions for a 2000-ton SES had been recorded at 20 samples per second. The outputs were recorded on a variety of media. For on-line monitoring, the MoGen motions were continuously plotted on an 8-channel pen recorder at slow chart speed. These and other test data signals were also recorded periodically on 16 channels of the NSRDC recording system. Along with its own test outputs, the Naval Aerospace Medical Research Laboratory Detachment at Michoud, LA (NAMRLD), recorded some of the motion signals on its FM tape recorder as a back-up to the other recordings.

In the cabins, ample illumination for desk work and reading was provided by lamps at each duty station to supplement the overhead lamp. Heaters and air conditioning controlled by the crew maintained a cabin temperature of about 70^{o} - 76^{o}F. The overall noise level in all parts of the moving cab with all pumps operating was about 71 ± 2 dBA; the comparable level for the stationary cab was 69 ± 2 dBA. A per-octave-

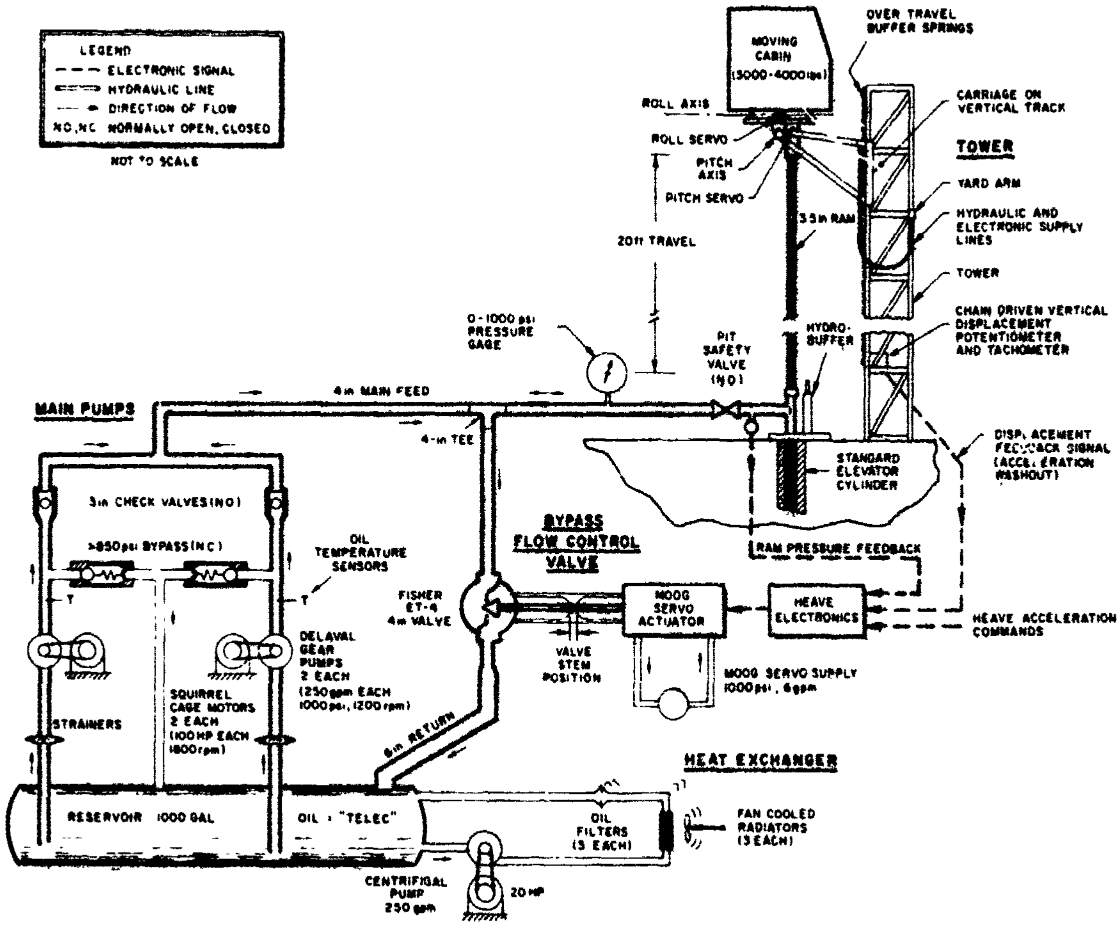


Figure 1. ONR/HFR Motion Generator Heave Drive Hydraulic System Functional Schematic (Fig. II-2, Vol. 2)

Table I

VERIFIED MOTION GENERATOR PERFORMANCE (1975)
(Table II-1, Vol. 2)

HEAVE:		
Limits:	Position	± 10 ft
	Velocity	± 18 ft/sec
	Acceleration	+ 1.0+ g (up), −0.9 g (dn)
Usable Bandwidth		0.1 to 5 Hz
Small-Signal Deadband		±0.04 g (0.1-5 Hz)
Effective Delay to Acceleration Commands		0.02 sec (minimum) 0.18 sec (Matched to roll and pitch axes)
Harmonic Distortion		
(Average over 20-80% Amplitude, 0.2 – 2.0 Hz)		< 10%
Overall Linearity (rms g's)		> 0.95
PITCH AND ROLL:		
Limits:	Angle	± 15 degrees
	Rate	± 25 deg/sec
	Acceleration	± 150 deg/sec^2
Bandwidth		0.1 to 4.0 Hz
Effective Delay		0.18 sec
Overall Linearity (rms rate)		> 0.95
Cross-Coupling Pitch/Roll		< 8%
Phase Matching to Heave (0.2-3.0 Hz)		< 1/20 cycle (< 20 deg)

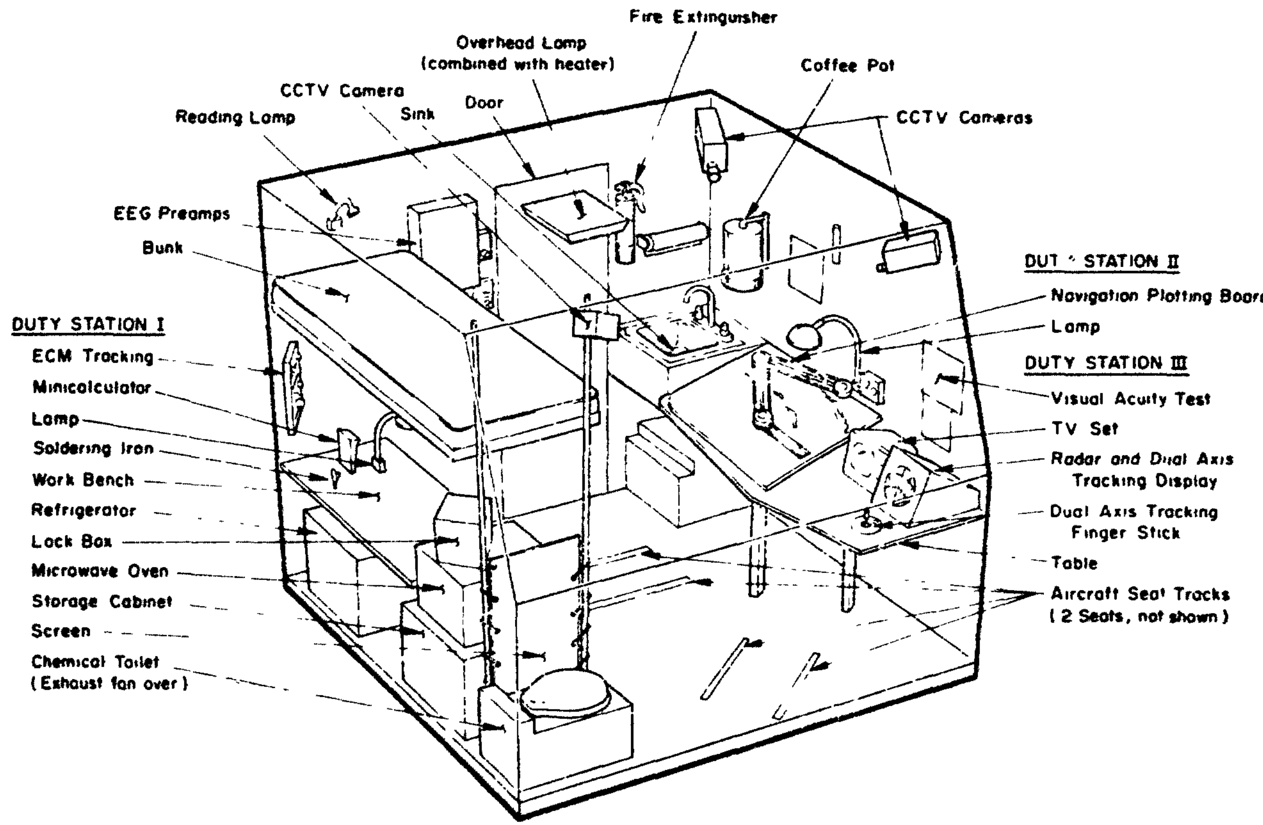
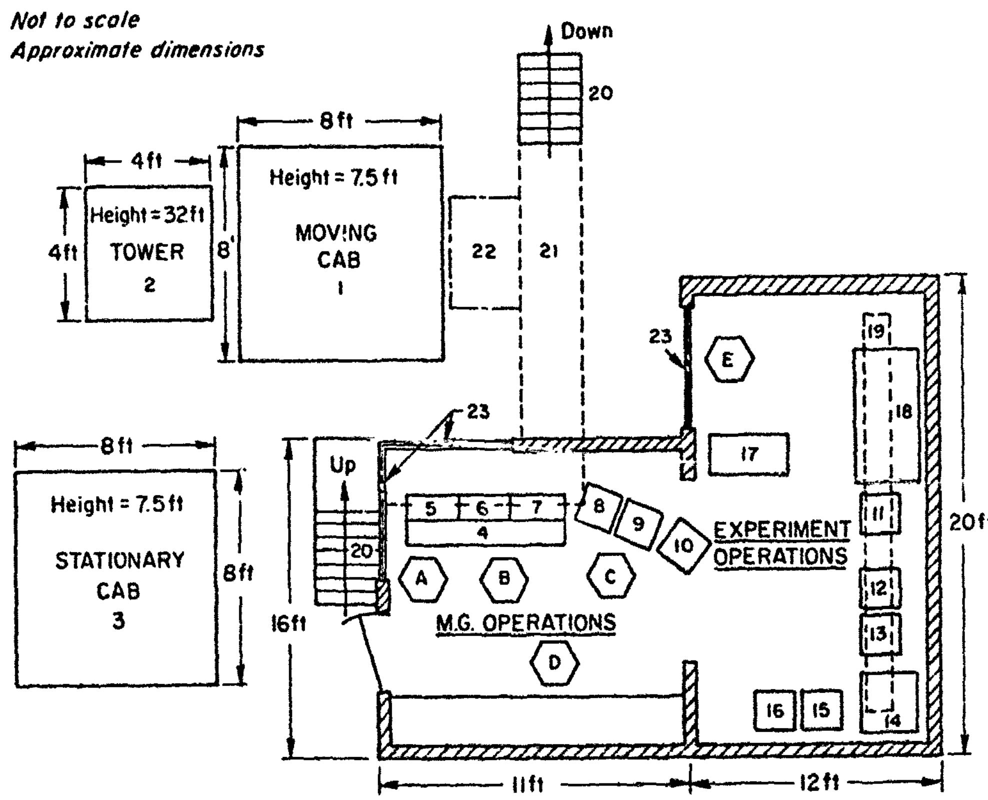


Figure 2. General Arrangement of Apparatus in Cabin for Phase II (Fig. II-7, Vol. 2)



LEGEND

1. Moving Cabin
2. Tower
3. Stationary Cabin
4. Communications and Task Monitoring Console
5. Voice Tape and Controls
6. Voice and T.V. Monitors
7. STI Task Panel
8. Motion Generator Operating Panel
9. Motion Generator Compensators and Patch Panel
10. Strip Chart Recorder
11. HFR Computer
12. NSRDC Digital Tape Recorders
13. NSRDC Digital Computer
14. NSRDC Disk Drive
15. NSRDC Teletype
16. NSRDC Line-Printer
17. NAMRLD Strip Chart Recorder
18. NAMRLD Equipment
19. Air-Conditioning Duct (Under Floor)
20. Stairs to Docking Ramp
21. Overhead Walk-way
22. Docking Ramp
23. 5 ft Wide Observation Windows

A. Medical Monitor
B. Task Conductor
C. Motion Generator Operator
D. Test Director
E. Observer/Support Personnel

Figure 3, General Arrangement of the ONR/HFR Motion Generator Facility (Phase II) (Fig. II-6, Vol. 2)

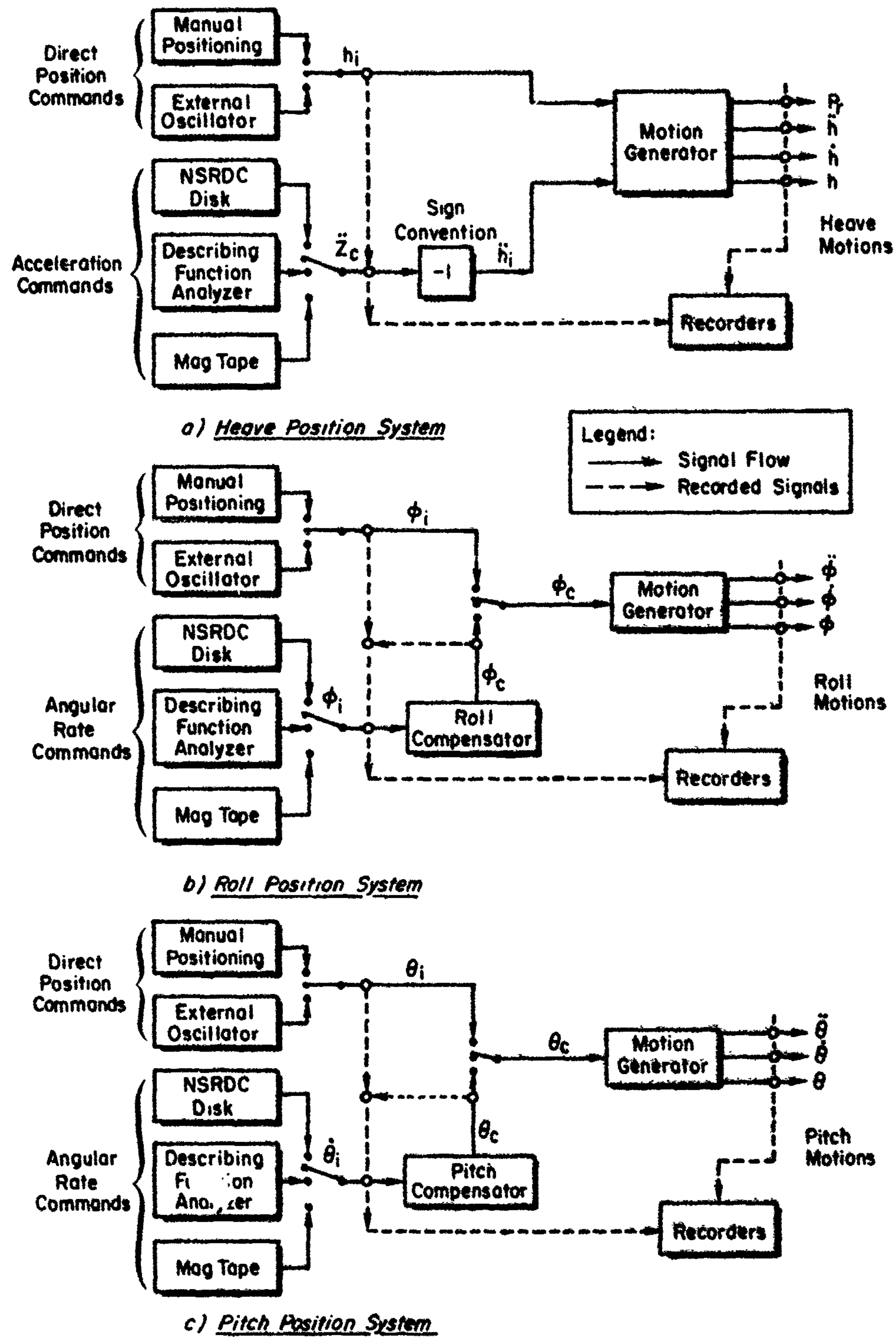


Figure 4. Inputs and Outputs of the MoGen During Phase II (Fig. II-4, Vol. 2)

spectrum-scan showed broadband distribution of noise over the 31.5 - 4000 Hz range, with a maximum of about 80 dB near the 63 - 125 Hz region. In summary, the living conditions in these cabins were cramped but not too unpleasant with respect to temperature and noise levels. Experienced observers noted that similar conditions exist in a number of shipboard or airborne situations.

CHARACTERISTICS OF MOTION CONDITIONS

The test objectives require that the simulated motion conditions closely approximate those worst-case motions of a large SES, and that they be analyzed in sufficient detail to identify motion characteristics which distinguish one condition from another. Also, the objectives demanded a formal matrix of test conditions and routines.

Experimental Design

The test plan provided for 12 subjects, divided into 6 two-man crews. Two crews formed a test team that would alternate between motion runs in a moving cabin and stationary runs conducted in a separate, identical static test cabin. The static runs were intended to provide a baseline of performance against which the effects of motion could be assessed. Limited resources and the exploratory nature of this study limited sample size to a minimum number. Subjects were also to be exposed to multiple conditions thus introducing an ordering effect and a selection effect both in terms of the original subjects and for any subjects that might be introduced as substitutes in later runs.

Motion and static runs were planned to be 48 hours in duration. This exposure time was selected as the minimum period over which subjects might be hoped to stabilize with respect to experimental conditions. (Increasing the length of motion exposure significantly increases the cost per data point; however, in retrospect, even longer periods may be required as motion levels are decreased toward that deemed desirable for acceptable habitability.) Motion conditions were to be highly repeatable to allow intercomparison of subjects exposed to a given "dose" of motion. It was known a priori that both the frequency and temporal content of the motions could significantly affect the impact of the motion exposure.

The motions were those predicted for the center-of-gravity of a 2000-ton SES traveling at design speed in starboard bow seas at sea states 3, 4 and 5. In some tests at the higher sea states the intensity of heave acceleration was reduced to simulate the effect of an active RCS. Motion severity was to be increased systematically for all subjects to facilitate any motion adaptation that might occur.

Following these tests, and based on their results, additional motion simulations were to be conducted using the same 12 subjects, plus 8 or 9 others, in order to expand further the motion effects data base.

Actual Conditions Tested

For a number of reasons, the original plan could not be implemented precisely: sporadic motion generator problems; miscalibrations resulting in excessively attenuated intensities; early withdrawal of some crewmen due to motion sickness; and a sample size which was sufficiently small to neither allow for significant loss of subjects or to supply strong statistical inference. As a result of these difficulties, several variations of the three originally selected full-scale conditions were necessary, with individual subject exposure times varying from 30 minutes to 48 hours. Actual conditions fell within the original test cell design for only a few subjects. *A posteriori*, all actual runs were grouped by sea-state/speed and, within a given heave-acceleration waveform, by the attenuation factor. This grouping resulted in a 3 x 3 matrix of which eight cells were run, as shown in Table II. Test conditions grouped in this manner are identified in the rest of this report by the "Source" tape used to generate them, preceded by the verbal descriptor of their intensity relative to that of the corresponding source condition and/or the nominal fraction thereof in parentheses. For example, "Low (2/3) SS3" refers to the upper, left-hand cell condition.

It should be noted that on one diagonal in Table II there are three different waveform conditions (SS3, SS4, and SS5) at a heave acceleration of 0.19 g_z rms. The attenuated SS4 and SS5 conditions were run as a sub-experiment to compare the effects of different frequency distributions having equivalent rms accelerations.

Summary of Conditions Simulated

The inputs for the heave acceleration, pitch rate, and roll rate signals were drawn from the same source tapes used during Phase IA: five-minute tapes generated by NSRDC using the mathematical model developed by Oceanics, Inc., for a generic 2000-ton SES. The mathematical model did not incorporate the motion attenuating capability of an active ride control system. As in the previous simulation, continuous motion over the course of each run was generated by playing the five-minute tape segments head-to-tail, with a two-second smoothing transition between segments. The most important motion statistics are summarized for the originally computed (source tape) conditions in Table III.

As shown in Table II, all motion conditions actually run were grouped into eight cells containing from 2 to 5 different runs each. One run from each cell was selected as representative of the motion characteristics of all runs in the cell. Heave acceleration statistics for these typical runs are provided in Table IV. Only 7 of the 8 cell conditions are represented fully, since accurate reduced data were not

Table II

Matrix of Test Conditions, Grouped
According to RMS Heave Acceleration
and Nominal Sea State Spectral Shape

(after Table III-1, Vol. 2)

Nominal Sea State Spectrum	Acceleration Intensity Level		
	"Low" (2/3)	"Medium (4/5)	"Full" (1)
SS 3/80 Kt	0.13 g 2 runs	0.16 g 5 runs	0.19 g 4 runs
SS 4/60 Kt	0.17 g 2 runs	0.19 g 4 runs (all 6-hour)	0.25 g 5 runs (three 6-hour)
SS 5/40 Kt	0.19 g 3 runs (all 6-hour)		0.28 g 5 runs (two 6-hour)

Note: All test runs were from 20 to 48 hours except for the 6-hour runs noted.

Table III

SUMMARY OF SOURCE TAPE (CALCULATED) MOTION STATISTICS
FOR GENERIC 2000-TON SES
(Table III-2, Vol. 2)

CONDITION	SEA STATE 3 AT 80 Kt			SEA STATE 4 AT 60 Kt			SEA STATE 5 AT 40 Kt		
NSRDC TAPE NO.	JR 21			JR 19			JR 12		
PARAMETER	σ	Max (Up) / Min (Down)	f_o^+ Hz	σ	Max (Up) / Min (Down)	f_o^+ Hz	σ	Max (Up) / Min (Down)	f_o^+ Hz
Heave Acceleration (g)	0.194	0.662 / -0.554	0.890	0.248	1.05 / -0.676	0.77	0.278	1.38 / -0.710	0.703
Heave Velocity (ft/sec)	1.47	4.03 / -5.19	0.676	2.30	5.47 / -8.80	0.537	3.24	7.26 / -12.77	0.427
Heave Displacement (ft)	0.514	1.36 / -1.62	0.472	1.01	2.58 / -2.97	0.343	2.17	5.85 / -5.91	0.203
Pitch Acceleration (deg/sec^2)	0.949	3.12 / -3.03	1.26	1.61	5.14 / -4.92	0.623	3.63	13.68 / -10.59	0.337
Pitch Rate (deg/sec)	0.286	0.837 / -0.813	—	0.751	1.99 / -1.94	—	2.44	6.11 / -5.44	—
Pitch Angle (deg)	0.180	0.479 / -0.558	0.244	0.523	1.30 / -1.21	0.210	1.87	4.52 / -4.28	0.200
Roll Acceleration (deg/sec^2)	0.278	0.953 / -0.890	2.05	0.651	1.97 / -1.73	0.863	1.32	3.38 / -3.61	0.377
Roll Rate (deg/sec)	0.0600	0.184 / -0.156	—	0.285	0.666 / -0.748	—	0.847	2.12 / -2.31	—
Roll Angle (deg)	0.0207	0.0567 / -0.0589	0.468	0.151	0.317 / -0.409	0.293	0.628	1.34 / -1.47	0.207

Notes:

1. All conditions reflect motion at the center of gravity in a starboard bow sea (ship's heading of 135 deg relative to direction of wave travel).
2. Sigma (σ) and the maximum and minimum values are taken about the calculated mean, whose deviation from zero is an artifact due to math-model mistrim.

Table IV

SOME HEAVE ACCELERATION CHARACTERISTICS OF GROUPED TEST CONDITIONS
(Table III-3, Vol. 2)

CONDITION	NAMRLD TAPE NO.	MOGEN RUN NO.	HEAVE ACCELERATION RANGE		RMS G_z OVER WHOLE SPECTRUM	RMS G_z OVER 0 - 0.56 Hz RANGE*	RMS G_z OVER 0.57-10.0 Hz RANGE*	CHARACTERISTIC FREQUENCY UP ZERO CROSSINGS	FREQUENCY OF EXCEEDING +0.5g LEVEL
			Max (Up)	Min (Down)	σ	$\sigma_{<.6}$	$\sigma_{>.6}$	f_0^+	$f_{.5}^+$
			(g)	(g)	(g)	(g)	(g)	(Hz)	(Hz)
Low (2/3) SS 3	SB 116	485	0.465	−0.335	0.126	0.0674	0.107	0.977	0
Medium (4/5) SS 3	SB 134	487*	0.613	−0.413	0.158	0.0853	0.134	0.933	0.0633
Full (1) SS 3	SB 143	489	0.695	−0.495	0.193	0.104	0.163	0.907	0.110
Low (2/3) SS 4	—	—	—	—	~0.17	—	—	—	—
Medium (4/5) SS 4	SB 233	530	0.864	−0.460	0.192	0.108	0.158	0.833	0.117
Full (1) SS 4	SB 236	540	0.978*	−0.579	0.250	0.142	0.206	0.790	0.170
Low (2/3) SS 5	SB 235	538	0.857	−0.431	0.191	0.121	0.148	0.730	0.103
Full (1) SS 5	SB 237	543	1.013*	−0.634	0.282	0.178	0.219	0.700	0.183

Notes:

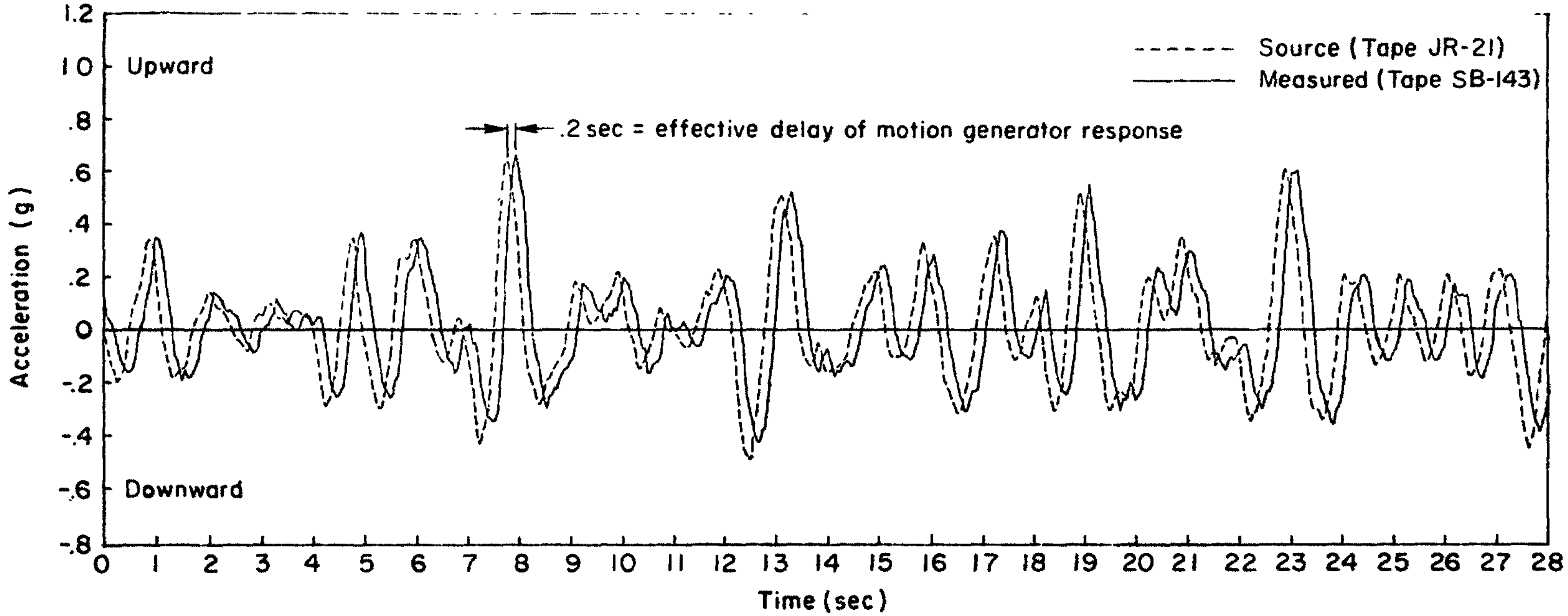
- Sigma (σ) and the maximum and minimum values are taken about the computed mean, whose deviation from zero is an artifact due to transducer bias.
- All values are measured; they do <u>not</u> presume Gaussian distributions.
- $\sigma_{<.6}$ includes ISO bands from 0.025 to 0.50 Hz (0.56 Hz upper edge); $\sigma_{>.6}$ includes ISO bands from 0.63 to 10.0 HZ (0.56+ Hz lower edge).
- $\sigma = (\sigma^2_{<.6} + \sigma^2_{>.6})^{1/2}$.

*Data recorded during first three hours of run prior to MoGen recalibration.

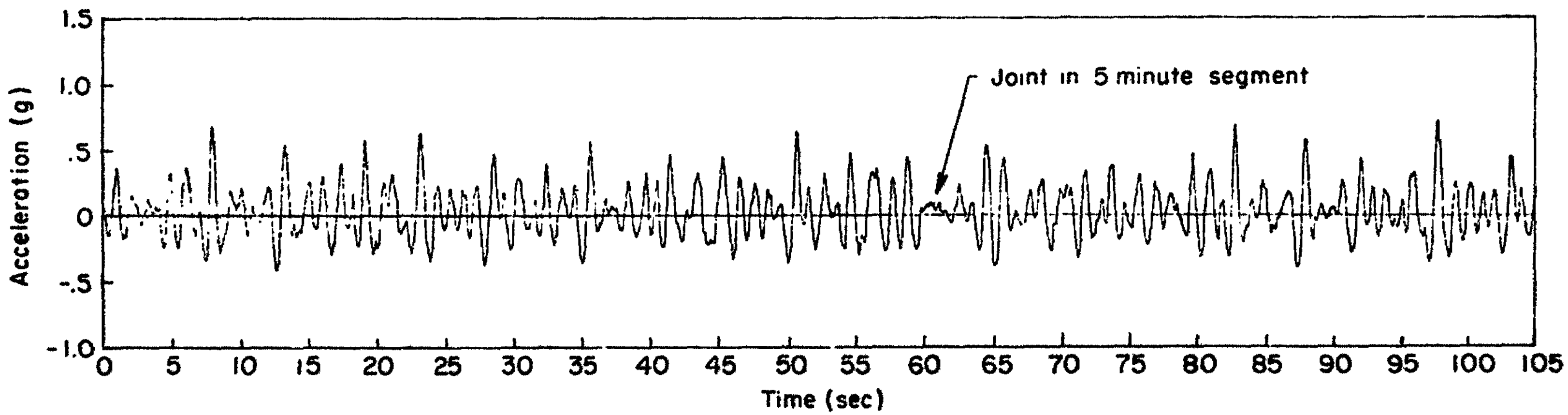
available for the low SS4 condition.

Volume 2 presents detailed comparisons between some tapes and measured motion data. In general, the analyses indicate that the heave and heave acceleration statistics of the measured data are reasonably representative of the source data. An example of a measured heave acceleration time series for SS3/80 kt is shown in Fig. 5, along with the time series from the source tape JR-21. Measured pitch and roll angular displacements also appear to be fairly well represented by their source counterparts, but large differences in pitch and roll rate, and even larger differences in angular acceleration statistics testify to the presence of high-frequency structural vibrations. While these modes do not appreciably affect angular displacement, which is a good indicator of relative motion effect, they do change the rms angular rates and accelerations. Nevertheless, these small vibratory motions were not apparent or annoying to the crew, and the match of angular motions is considered acceptable.

In summary, during Phase II the upgraded ONR/HFR Motion Generator provided motions representative of those calculated for a generic 2000-ton SES at three tested sea state/ship speed operating conditions, accurately reproducing the heave motions which dominate these conditions with great fidelity over their respective range of interest (roughly 0.16 to 1.6 Hz).



a) Comparison of Source and Measured Waveforms



b) Typical Measured Waveform

Figure 5. Heave Acceleration Time Histories for Source and Full Measured Starboard Bow Sea State 3/ 80 kt Conditions

TEST SUBJECTS

Recruitment Procedures

The 19 volunteer subjects used in Phase II came from a group of 26 men qualified for biodynamics research and attached to the NAMRL Detachment. Recruitment of the 26 volunteers involved: (1) Bulletin board advertisement of the program; (2) A presentation to interested recruits; (3) Interview of those with a continuing interest; (4) Identification of a volunteer candidate group on the basis of the interview; (5) Initial screening of the candidate group by review of dental, medical, and administrative records, and X-rays of lower back; (6) Two weeks of intensive medical evaluation of the remaining candidates for final selection. The carefully screened and self-selected final group represented a selection rate of 4.3 percent from a total of 600 interested recruits.

Qualification of Subjects

Volunteer subjects at the NAMRL Detachment perform duty as experimental subjects in experiments utilizing acceleration or deceleration devices, and qualify for hazardous duty pay. Each subject must be demonstrated to be free of any defect that would increase his susceptibility to injury under this specific experimental stress before the subject is ever used in an experiment. The qualifications are considerably more stringent that the normal medical qualifications for military service or for various other categories of experimental stress duty. For Phase II testing, those with anomalous vestibular response were also excluded.

Most of the subjects used in Phase II were just out of boot camp, with little, if any, naval sea duty at the time. Three teams, comprising seven members each, served as subjects for about three weeks each. Four of each team were selected as the primary test group; the others served as backups. Selection of primary crewmen was based on (1) satisfactory task learning and motivation demonstrated during the training period, (2) any minor illness (as a negative factor), and (3) likely compatibility of cabinmates, as indicated by each trainee.

MEDICAL MONITORING

A medical officer was at the test site at all times while the simulator was in motion with a human subject aboard. The medical officers from the NAMRL Detachment had extensive professional knowledge of each subject, supported by detailed medical records, as a result of the selection procedures and utilization of the subjects for impact acceleration experiments. In those sled tests, seven subjects had run to 15 g, three to 10 g, two to 6 g, and seven to 3 g.

The primary record of observation was the medical log in which all on-site medical observations were recorded. These observations include pre-run and post-run medical examinations.

Secondly, electrophysiologic measurements were recorded on magnetic tape: one channel of electroencephalogram, two channels of electrocardiogram, one channel of electromyogram for the neck, and two channels of head acceleration used in their analysis to control for motion artifact. Various segments of a one-channel electrocardiogram were recorded on demand by the medical officer; these records were not given any systematic analysis since no abnormalities were noted.

The third monitoring procedure consisted of measuring head accelerations using a mouth-mounted T-plate carrying six accelerometers. The purpose of these measurements was to determine the inertial response of the head to cab motion and to determine whether there was any postural control of the head by the subject in response to feelings of motion sickness. These measurements were scheduled every 12 hours on each subject in motion and were made with subjects in both sitting and standing positions. If motion sickness symptoms were, or seemed as though they might be, aggravated by the mouth mount, measurements were stopped. (The analysis of these measurements is to be presented in a separate report.)

The fourth monitoring procedure was part of the subjects' task performance; each subject periodically recorded his own oral temperature and the blood pressure of his crew partner. Review of these records by the medical staff, NAMRL Detachment, revealed no significant changes.

In addition, periodic urinalyses were done on small aliquots and were recorded in the medical log.

TEST SCHEDULES

The Phase II simulation was accomplished over three consecutive one-month intervals, corresponding closely to the calendar months of July, August, and September 1975. The first week of each month was set aside for maintenance and checkout, and preparation for that month's tests. During the second week, that month's "team" arrived at the testing site. In a few days, all seven were trained on the various tasks and tests to be presented during the experimental runs, and each was given a 15-minute "sampler" motion run: five-minute segments at each of the three full conditions (SS3, SS4, and SS5). Experimental runs occurred during the last three weeks of each month.

Most experimental runs were scheduled for 24 or 48 hours, the only exceptions being the six-hour, mid-September ones. In general, the moving cabin was continuously driven by the MoGen during all motion runs except for occasional brief stops to attach electrodes to subjects just prior to sleep periods, to remove subjects prematurely terminating a run, or to install replacements for subjects who aborted. Occasionally, longer stops (up to several hours) were caused by MoGen problems.

The work/rest schedules for the formal runs assigned specific intervals for the performance of various tasks, for the measurement of certain physiological variables, for attending to routine life support functions, and for free time for relaxation and recreation. Schedules were interlaced for each pair of subjects to avoid any interference that might occur during formal activities in the limited cabin space.

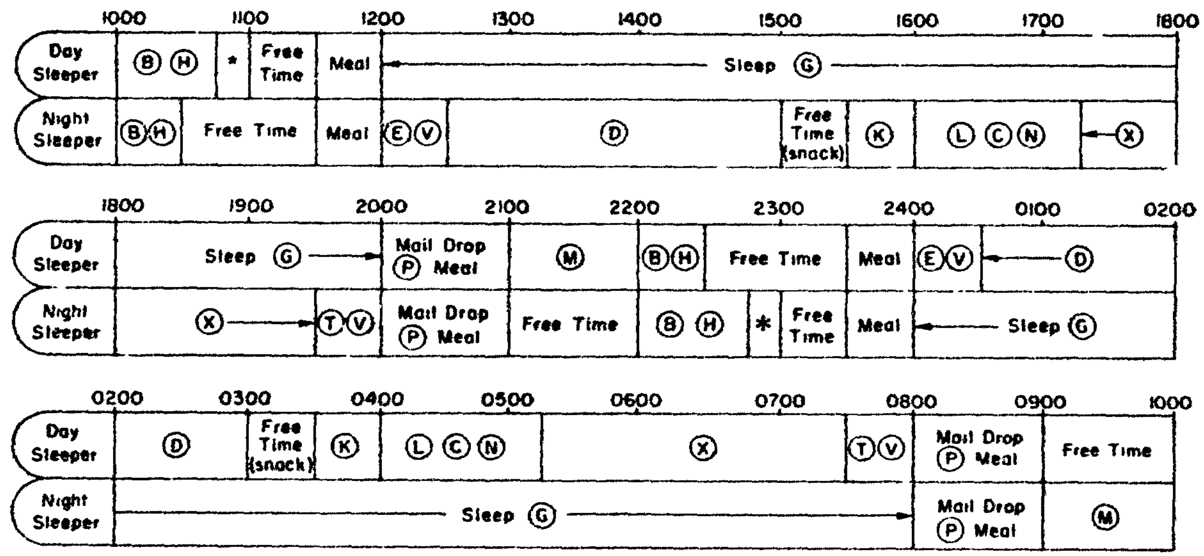
The tasks, tests, and measurements are listed in Table V in the order of the alphabetical code used to identify the activities on the work/rest schedules shown in Figure 6. The schedules represent the planned routines and also typify the resulting practice. However, due to difficulties mentioned earlier, there were some unavoidable deviations from plans. A summary of conditions, run deviations, and reasons for run terminations during the three month Phase II program is presented in Table VI.

Table V

SUMMARY OF TASKS AND MEASUREMENTS
(Table IV-1, Vol. 2)

CODE	NAME	DESCRIPTION	DUTY STATION*	RESPONSIBLE ORGANIZATION	RESULTS IN VOLUME
B	Blood Pressure Measurement	Sphygmomanometer measurement of systolic pressure, sitting	I, III	HFR	4
C	Cryptographic Task	Manual decoding and encoding of written messages	I	HFR	4
D	Missile Detection Task	Air surveillance radar watch (low contact frequency)	III	HFR	4
E	ECM Tracking Task	Antijam Frequency Meter tracking using MK VII 1st-order autopaced Critical Task, dial display, unrestrained knob control	I	STI	3
G	Sleep State Measurement	Electrophysiological monitor of sleep pattern	bunk	HFR/NAMRLD	5
H	Head Motion Measurement†	6-axis miniature accelerometer package, on combination bite-head clamp. Subject assumed various postures sitting and standing while data recorded	III	NAMRLD	5
K	Keyboard Task	Calculating closure rate, intercept time, speed and relative bearing of an approaching object using a minicalculator	I	STI	3
L	Lock Task	One handed opening of a precision four combination lock	I	STI	3
M	Maintenance Task	Disassembling a power supply circuit card using only soldering iron, pliers, and screwdriver	I	STI	3
N	Navigation Plotting Task	Plotting own ship's and radar target positions and courses	II	HFR	4
P	Load Task†	Handling a 13 lb "box" of electronic rack dimensions	I	STI	3
T	Dual Axis Tracking Task	Compensatory tracking of a target using a finger stick and elevation azimuth display	III	STI	3
V	Visual Acuity Measurement	Reading of near point printed material of varying size	III	HFR	4
X	Collision Avoidance Task	Radar watch of nearby ships in heavily trafficked area	III	HFR	4

*Per Fig. II-7 (cabin layout).
†Done only under motion conditions.



*MoGen stopped for 10-15 minutes while electrodes are attached to subject for G.

Notes

- Circled task or measurement codes are defined in Table IV-1.
- Subjects voided in specimen bottles just prior to and right after their sleep periods providing "wake" and "sleep" urine samples for catecholamine analysis used to measure stress.
- Cabin temperature and oral temperature of nonsleeping subjects were measured at, nominally, 4 hour intervals beginning at 1200. Subjective evaluations of sleepiness and of various habitability factors were given at this time. Habitability ratings were also scheduled 30 and 90 minutes into each run regardless of start time
- The load task, P, the head motion measurement, H, and the habitability ratings were given only under motion conditions

Figure 6. Daily Work/Rest Schedule for Long Runs (Fig. IV-2, Vol. 2)

Table VI

SUMMARY OF CONDITIONS (INPUT WAVEFORMS AND NOMINAL LEVELS), OVERALL ACCELERATIONS, SUBJECTS, EXPOSURE TIMES, AND REASONS FOR TERMINATION (Table 2, Vol. 4)

CONDITIONS				SUBJECTS[1]		EXPOSURE TIME (HOURS)[2]	
INPUT WAVEFORM	NOMINAL LEVEL	RUN NO.	OVERALL ACCELERATION (rms g)	DAY SLEEP	NIGHT SLEEP	0 8 16 24 32 40 48	REASON FOR[3] TERMINATION
80 Kt, SS3	Low	483	.127	43	50		S S
		485	.127	39	48		S S
80 Kt, SS3	Medium	424	.155	44	49		E E
		439	.149	47	52		S M
		440	.149	44 38	49		S M S
		455	.168	38	46		M M
		457	.168	35	49		S S
80 Kt, SS3	Full	487	.193	50	43		E E
		489	.193	48 51	39		S M S
		525	.193	60	40		S S
		527	.193	56	61		S S
60 Kt, SS4	Low	453	.170	38	46		S S
		454	.170	47	49		S M
60 Kt, SS4	Medium	529	.192		43 59		S S
		530	.192	40 51			S S
		532	.192		56 60		S S
		533	.192	61 57			M M

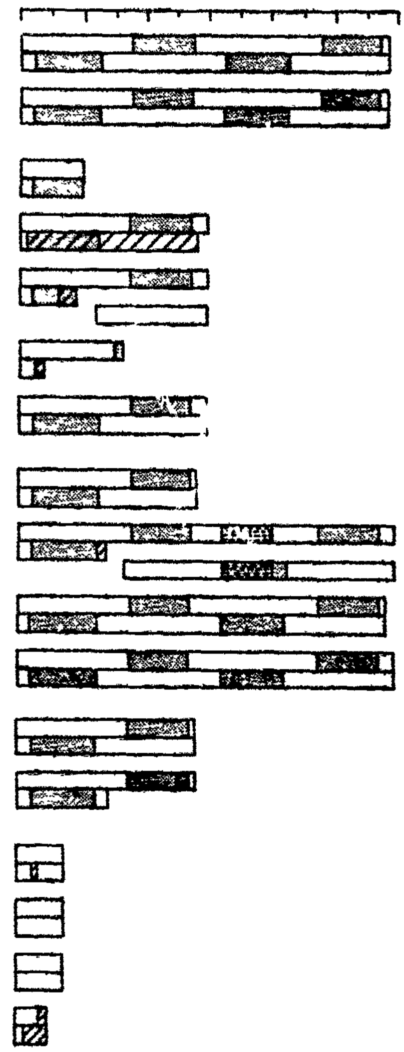
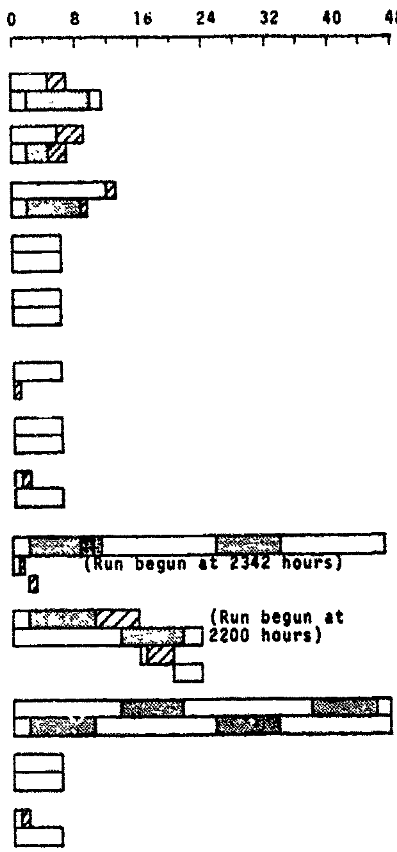


Table VI (continued)

CONDITIONS: INPUT WAVEFORM	CONDITIONS: NOMINAL LEVEL	RUN NO.	OVERALL ACCELERATION (rms g)	SUBJECTS: DAY SLEEP	SUBJECTS: NIGHT SLEEP	REASON FOR TERMINATION
60 Kt, SS4	Full	446	.221	47	52	M E
		451	.221	47	49	M M
		550	.248	60	40	M M
		540	.248		43 60	S S
		541	.248	40 51		S S
40 Kt, SS5	Medium	535	.191		43 59	S M
		536	.191	40 51		S S
		538	.191	56 60		M S
40 Kt, SS5	Full	494	.254	50 48	43	S M M
		496	.254	51	39 58 43	M E M E
		547	.287	43	51	S S
		543	.287		43 60	S S
		545	.287	40 51		M S

EXPOSURE TIME (HOURS)



[1]Subject numerically coded by Naval Aeromedical Research Laboratory Detachment (NAMRLD).

[2]Exposure time identified with respect to scheduled activity and subject condition: open space--waking period and subject apparently normal; shaded space--sleeping period and subject apparently normal; crosshatched space--subject sick or severely nauseated; dashed lines--temporary machine breakdown.

[3]Reasons for termination: S--scheduled termination; E--equipment failure; M--subject aborts due to motion sickness.

VISUAL-MOTOR TASKS AND RESULTS

Overall Conditions

The various tasks given in Phase II were selected as being typical of a wide range of shipboard tasks, yet simple enough to learn in the brief training period preceding formal runs. Wherever possible, each task was given a "scenario" or content relevant to SES operations. For example, the ECM task operator was told that his task simulated an ECM operator trying to prevent increasingly rapid radar frequency shift jamming by an approaching enemy aircraft or missile. Although the crude scenarios would not suffice for experienced personnel, they worked very well to motivate the relatively inexperienced crewmen involved.

After being introduced to each task, the crewmen practiced it twice (generally several trials per session) and those who had trouble were generally given extra practice. Thus, each of the four primary crew members was trained in any given task, although not always to an asymptotic level of performance due to time limitations. Data from the static runs were collected to serve as a baseline for separating motion effects from learning effects.

Electronic Countermeasure (ECM) Tracking Task

This task requires centering a needle on a dial by use of a freely turning knob underneath, with the subject's arm out-stretched and unbraced. Continuous correction is required and the degree of instability is increased to simulate decreasing enemy range. The operator "holds lock" as long as possible, typically 20 - 30 seconds. At some intermediate range, an anti-missile "Missile Away" light informs the operator that he is performing well. The operator's score is the degree of instability (λ_c) at which control is lost. Immediate score feedback was given to the operators, and an incentive prize was promised for those subjects who achieved a 5-trial median score of 5.0 or more. Five trial runs were employed and the control test took 4 - 8 minutes.

Specific findings and conclusions based on analysis of the results are as follows:

- At about 0.05 to 0.10 g_z rms, performance begins to fall off, reaching a 15 to 20 percent decrement in the range of 0.15 to 0.30 g_z rms; degree of decrement is independent of the motion spectrum as long as major power is in the 1 - 3 Hz range.

- With experience in a given sea state, most subjects gradually bring performance up toward, but not to, the static baseline level.

- Among the few subjects available for comparison, there is a fairly consistent trend showing improved performance at higher sea states and ampltiudes relative to lower sea states; this trend may be due to adaptation, since Full Sea States 4 and 5 were always the last to be experienced.

- Differences among subjects are greater than differences in task performance due to the applied motions, and the better performers generally seem to adapt most readily to motions.

- As shown by ECM tests completed by eight crewmen just before they aborted their runs due to motion sickness, performance can be maintained at levels typical of the motion condition until severe nausea and emesis occur.

Dual-Axis Tracking Task

The scenario for this task is that of a crewmen providing backup tracking for a remotely located anti-aircraft gun or multiple-missile launcher. Using a two-axis finger-stick, he "directs the weapon" in elevation and azimuth by attempting to center a pipper both horizontally and vertically on a CRT display. Duration of tracking is about two minutes, but performance is scored only from the tenth to the 110th second to avoid starting and ending effects. Three two-minute trials constituted a test, except for trials that were repeated when control was lost to a criterion in less than 50 seconds of scoring time.

Specific findings and conclusions based on analysis of the data are as follows:

- In nearly every case in which static-motion comparisons were made, all crewmen showed a decrement in tracking accuracy during motion; this decrement varied from 16 percent at low SS3 to 56 percent at full SS5.

- A strong correlation (ρ = 0.8 - 0.9) between accuracy and characteristic frequency (of upward zero crossings) was found across all static tests.

- Vertical tracking accuracy was roughly 40 percent worse than horizontal for all conditions, including most static cases.

Keyboard Task

The Keyboard Task is designed to test the motion sensitivity of keyboard operations such as might be typical of small on-board computers. The task scenario is that of determining the collision potential of an approaching "target." Using a wall-mounted minicalculator, the crewmen computes time-to-intercept, rate-of-closure, target speed, and relative ship-to-target heading. This task was done in three-problem tests, with knowledge of results at the end of the three trials. Mean computation time for the three trials was the basic measure of performance; also recorded were number of wrong answers and number of times the computation had to be reinitiated due to recognized miskeying.

Analysis of the results showed the following:

- Under static conditions, the median computation time for all subjects improved from about 125 to 80 seconds, with an 8-day learning time constant.

- On the average, there was less than 1.0 computing error per problem, with no apparent pattern due to either static or motion conditions.

- In the only two conditions where sufficient data exist for matched pair comparisons between motion and static trials, motion increased computation times by 24 percent in medium SS4.

- In SS4 conditions, subjects who indicated "no symptoms" of kinetosis retained performance within 20 percent of static levels, while those who had severe motion sickness dropped more than 40 percent in performance.

Lock Task

This task requires dialing the four-number combination of a low-friction, precision, combination lock, using only one hand and holding the arm outstretched. The primary measure of performance is the time required to correctly open the lock; the number of restarts is used as a supplementary measure. About 5 minutes were required for each lock opening test.

Specific findings and conclusions are as follows:

- Data for the static condition clearly indicate continued learning throughout the test program, with roughly a 3-day learning time constant.

- Under static conditions, the basic opening time was around 19 seconds, with 45 percent restarts, for a median time of 26 seconds among all subjects.

- Only the least severe motion condition (low SS3) showed little change from static. Under all other motions, there was a 10 percent increase in opening time and 38 percent more restarts for most subjects and conditions, but no systematic pattern which could be correlated with motion properties.

- The tendency for worse performance under motion was highly significant statistically.

Maintenance Task

This task requires the removal of both mechanical (e.g., screws, nuts) and electrical (e.g., resistors, capacitors) parts from a standard power supply circuit board. The only tools used are a soldering gun, needle-nose pliers, and a standard screwdriver. Performance was measured by a weighted disassembly rate, with intact parts given twice the weight of damaged parts. A maximum of 30 minutes was allowed for the task.

Specific findings and conclusions for the Maintenance Task are as follows:

- There was a wide range of individual performance and gradual improvement throughout the test period.

- About 75 percent of the cases showed a decrement in disassembly rate under motion, and 25 percent showed an increase, with the median going from 2.6 parts/minute static to 2.0 parts/minute under all motions.

- There was no systematic effect on disassembly rate among various motion conditions.

Load Task

The load used in this task was a 14-pound wooden box similar in outline to a rack of electronic equipment. This load was passed up to the crewmen via a large canvas bag, maneuvered through the sidewall hatch of the cabin, thence through a series of prescribed positions simulating various load-handling postures, and returned thereafter via the same bag on its return journey. No objective score was assessed for the Load Task because the results from earlier simulations had shown that no useful performance score could be measured: crewmen merely worked harder to compensate for motion interference. The task was added to Phase II in August after debriefing comments indicating that there was insufficient basis on which to evaluate load handling on the questionnaire completed by each subject.

SUBJECTIVE EVALUATION

General Considerations

Some of the task results showed that small decrements in performance may be the result of extra effort by crewmen to compensate for motion interference, and this effort can best be measured introspectively. In the Habitability Evaluation Questionnaire, three categories of subjective evaluation were assessed: (a) "Kinetosis" (motion sickness); (b) "Overall Environmental Rating"; and (c) "Specific Task Interference." Since a primary objective of the habitability ratings was the determination of any progressive effect of motion, assessments were scheduled periodically through each run; however, the schedules were not rigorously maintained. To assure independence, each evaluation was made on a fresh form which was deposited in the mailbox upon completion. See Figure 7.

Kinetosis Ratings

Kinetosis was rated both "globally," in terms of degree of kinetosis, and "diagnostically" to identify specific symptoms. Formal ratings were scheduled at 0.5, 1.5, and 6 hours after the beginning of motion for each subject, and at 4-hour intervals thereafter except during a subject's regular sleep period. Ratings of overall kinetosis were also logged in the Test Conductor's notebook and/or the Medical Officer's log from time to time.

The data showed the following trends:

- Roughly one-third to one-half* of each team became sick or quit due to sickness in SS4 or SS5 conditions, where the MSI (Motion Sickness Incidence) - weighted rms heave acceleration, σ_{MSI}**, exceeded about 0.05 g (corresponding to roughly more than 0.20 g rms, total). No emesis occurred in the few cases of low SS3, where $\sigma_{MSI} = 0.02$ ($\sigma_{g_z} = 0.13$).

- The correlation of worst kinetosis ratings during a run with σ_{MSI} was broadly scattered but not inconsistent with the trend of MSI vs. σ_{MSI}.

*Fraction of total runs as opposed to total subjects. See Table VII.
**For a discussion of MSI weighting, see Appendix A and Volume 3.

HABITABILITY EVALUATION QUESTIONNAIRE

Note. Numbers in parentheses are used for scoring; Not on subject's form

PHASE II   RUN NO.____

CREWMAN____________________ DATE: ___/___/___ (YEAR MONTH DAY) TIME ___:___ HRS. INTO MISSION ______

(Put any additional comments on reverse side.)

A. KINETOSIS (MARK THE SCALE)

LEVEL:	RATING	
NO SYMPTOMS	0	(1)
STOMACH AWARENESS	1	(2)
MILD NAUSEA	2	(3)
MODERATE NAUSEA	3	(4)
SEVERE NAUSEA	4	(5)
EMESIS OR RETCHING	5	(6)

COMMENTS: ____________

CHECK YOUR TENDENCY TO:

	NONE (1)	SOME (2)	PRONOUNCED (3)
1 YAWN A LOT			
2 SALIVATE, SWALLOW			
3 BELCH, BURP			
4 SWEAT			
5 MALAISE			
6 SKIN PALLOR			
7 WEAKNESS, TREMBLING			

	NONE (1)	SOME (2)	PRONOUNCED (3)
8 HEADACHE			
9 NAUSEA			
10 VOMIT OR GAG			
11 LOSS OF APPETITE			
12 CONSTIPATION			
13 LETHARGY			
14 SORE MUSCLES			
OTHER____			

B. OVERALL ENVIRONMENTAL RATINGS (MARK THE SCALE WHERE APPROPRIATE)

EFFECT ON YOUR WELL-BEING BY:

		WHOLE BODY MOTION	VIBRATION	SOUNDS	TEMP.
PLEASANT	Very	(1)			
	Slightly	(2)			
NO INFLUENCE		(3)			
UNPLEASANT	Slightly	(4)			
	Moderately	(5)			
	Extremely	(6)			
INTOLERABLE		(7)			

INTERFERENCE WITH SHIPBOARD DUTIES BY:

		WHOLE BODY MOTION	VIBRATION	SOUNDS	TEMP.
IMPROVEMENT	Much	(1)			
	Slight	(2)			
NO INFLUENCE		(3)			
INTERFERENCE	Slight	(4)			
	Moderate	(5)			
	Extreme	(6)			
INCAPACITATING		(7)			

C. SPECIFIC TASK INTERFERENCE (RANK THE DEGREE OF INTERFERENCE THAT THE ENVIRONMENT HAD ON THE TASKS BELOW: 0 = NEGLIGIBLE (1); 1 = MODERATE (2); 2 = EXTREME (3))

GENERAL FUNCTIONS:

EAT: HAND FOOD (SANDWICH)___; THICK FOODS___; LOOSE FOODS___;
DRINK: FROM CLOSED CONTAINER___; OPEN CUP___; POUR HOT COFFEE___;
READ: LARGE PRINT___; FINE PRINT___; FINE DIAGRAMS___; CALCULATOR READOUTS___;
WRITE: LARGE PRINTING___; SMALL PRINTING___; SCRIPT___; FINE DIAGRAMS___; PLOTTING___;
REST: RELAX, SNOOZE IN CHAIR___; SLEEP IN BUNK, UNRESTRAINED___; SLEEP IN BUNK, RESTRAINED___;
GO TO SLEEP QUICKLY___; AWAKE REFRESHED___;
MOVE ABOUT: WITH HANDHOLDS___; UNAIDED___; CLIMB LADDERS___; DESCEND LADDERS___;
CARRY LOADS: WITH TWO HANDS___; ONE HAND___; UP AND DOWN LADDERS___;
LAVATORY: WASH HANDS___; TOILET--SITTING___; TOILET--STANDING___; SHOWER___;
RAZOR SHAVE___; ELECTRIC SHAVE___;
RECREATION: CARD GAMES___; MODEL KITS___; SEWING REPAIRS___; TV___;

MISSION FUNCTIONS:

READ DISPLAYS: DIGITAL___; ON CRT___; ON METERS___;
CONTROL TASKS: SWITCHES___; PUSH BUTTONS___; KEYBOARDS___; STEERING___;

EXPERIMENTAL TASKS:

NAV. PLOTTING___; COLLISION AVOID___; MISSILE DETECT___; CRYPTO___; ACUITY___; LOCK-OPENING___;
ECM TRACKING___; 2-AXIS TRACKING___; KEYBOARD___; ELECTROMECHANICAL REPAIRS___;

Figure 7. Habitability Evaluation Questionnaire (Version Used by July and August Teams) (Fig. III-1, Vol. 3)

- There was evidence of a more gradual kinetosis progression in SS3, a pronounced drop in SS4, and a precipitous drop in SS5. Six-hour runs would expose only about half of the potentially sick subjects in SS3 and SS4, but almost all in SS5.

- The time course of terminal motion sickness toward emesis varied widely among sick crewmen with a common tendency to have mild symptoms followed by a divergent drop to "severe nausea" or "emesis" levels with a 2 - 4 hour time constant.

- There was not a concensus of opinion regarding subject adaptation to the motions.

Reaction to Various Environmental Factors

It was anticipated that under severe motion conditions or on very warm days, various cabin environmental factors might become annoying or exacerbate any kinetosis tendencies. To check this possibility, the influence of "Whole Body Motions," "Vibration," "Sounds," and "Temperature" on the "sense of well-being" and their "interference with shipboard duties" was rated every four hours.

The ratings showed that there were no serious complaints about any of the ambient conditions except whole body motion. The bunk area at the top of the cabin tended to become warmer than desirable, but the vent fan helped remove the warm air. There was an appreciable amount of vibration and noise in the moving cabin, mostly in the range of 25 - 100 hz; however, these effects are in a range similar to the machinery sounds and vibrations aboard ship and therefore did not have a totally extraneous effect.

Not all crewmen carefully logged these ratings, and it is suspected that some merely checked off all items the same (no influence) under most conditions.

Interference with Specific Tasks

Many subjects failed to complete this part of the Habitability Evaluation Questionnaire, and some who did were obviously not doing it carefully; therefore, much of this potentially valuable information was lost, and some of the data obtained are suspect. Furthermore, for several of the September runs, the questionnaire was inadvertently not given to the subjects. As a result of the various problems, only about half of the intended task interference data were obtained.

Confinement and ambient conditions were thus judged to have a tangible but unmeasured effect.

COGNITIVE TASKS AND RESULTS

Overall Considerations

For the tasks discussed in this section, performance depends heavily upon higher-order cognitive processes such as attention, perception, and memory, but not primarily upon motor coordination and control. These tasks were designed to simulate operational tasks, and each was given an operational scenario as described below. Each of the subjects was individually briefed, then trained by one of the Test Administrators on three consecutive days prior to the commencement of static or motion runs. For the cognitive tasks, training was continued until a specified criterion score was attained.

As reported earlier, frequent planned and unplanned modifications of the experiment design were occasioned by equipment malfunction and an unexpectedly high incidence of motion sickness among subjects in the more severe motion environments. The net result of these problems was a fragmentary and recognizably biased data base. Furthermore, the planned objectives of static exposures to provide baseline performance levels and to control for the effects of confinement and time-dependent factors such as learning and boredom were only partly achieved. The least equivocal data were obtained in the full SS3 condition. The data obtained from the eight subjects who completed at least one 24-hour exposure to that condition may be regarded as the most complete and unbiased for determining some effects of a type of simulated SES motion. For that reason, inferential statistical analyses were applied principally to those data. For the remaining conditions, the results of performance testing were treated mainly in a descriptive manner.

Radar 1: Missile Detection

This task was designed for measuring human ability to maintain attention in a simulated sea-surveillance radar watch wherein critical contact frequency is relatively low, and monotony is an intrinsic factor limiting performance effectiveness. The task scenario was selected to represent the detection of incoming surface-to-surface missiles closing at high speed. Imagery was presented on a 9-inch CRT in standard ship-centered, PPI format, with continuous video noise and the occasional missile contacts, which started at the periphery of the display at randomly selected bearings and moved on straight-line courses toward the display center. Upon detecting the contact, the subject pushed a DETECT button and verbally indicated the contact's bearing. His score was the number of verified contact repaintings before detection, up to a maximum of 12 for the 1-minute travel time. Each test was divided into three parts: (1) a 10-minute Pretest with 6 contacts; (2) a 2-hour Long Watch, with 6 contacts in each consecutive 20-minute period; and (3) a 10-minute Post Test, with 6 contacts. Training for Radar 1 was to a criterion of at least 80 percent detection in less than 7 sweeps with less than 10 false detects. In the static experimental runs, there was no evidence of general improvement due to further learning.

Comparison of the results for the static condition and all motion conditions showed no general adverse effect of motion upon target detection performance in any part of the task. If anything, performance was generally better in all of the motion conditions than in the initial static condition. Better performance under motion was probably attributable to greater motivation in the more challenging environment. Only one subject reported symptoms of motion sickness at the time of test administration. He vomited before, during and after the task, but he performed better (Pretest) or almost as well (Long Watch) as he did in the Static condition. Nearly all of the other subjects who became sick withdrew before their first scheduled test.

While the small sample sizes in most of the motion conditions precluded inferential statistical tests, it seemed meaningful to test the differences between static and motion performance at the full SS3 because 8 subjects completed a 24-hour exposure during which each experienced one test. Five of these 8 also completed a second test during their subsequent day of exposure. Statistical analyses showed that performance in the Pretest was significantly better in the motion condition for both tests, but that neither Long Watch nor Post Test performance levels differed significantly between conditions.

Even though these results fail to show any adverse effect of motion upon radar monitoring performance, no general conclusion seemed warranted. There is no way to determine from these results how sick individuals might have performed if they were compelled to attempt the task. The performance of individuals who were not sick seemed generally unimpaired by the motion, at least in full SS3. From this, it seems that motion sickness is the limiting factor in determining how men can be expected to perform monitoring tasks (and probably most other tasks) during 24- to 48-hour exposures to similar motion environments.

Radar 2: Collision Avoidance

The purpose of this task is to measure human attention and the ability to make complex perceptual discriminations in a simulated radar watch wherein the objective is to detect impending ship/ship collisions in a heavily congested area. Information overload is an intrinsic factor limiting performance effectiveness. Subjects viewed the radar imagery as in Radar 1, except that the display was that of a $\pm 60^\circ$ forward sector scan with the center at the bottom of the display. The sweep line traversed the sector for 1.67 out of each successive five-second interval, painting 18 to 25 contacts without video noise. Most simulated contacts were benign, but the benign contacts could become threatening at any time as a consequence of a course change. Other threatening contacts appeared first at the display periphery and remained on a collision course. The subject was required to report threatening contacts by pressing the DETECT button and verbally indicating the contact's approximate range and bearing. His verified response was scored as the percentage of collision course yet to be traversed before collision. Each test was 2 hours long and was divided into 30-minute periods; each such period contained 6 threatening contacts. Training for Radar 2 was essentially the same as for Radar 1.

Data for nine subjects showed no statistically significant difference between performance on Day 1 and Day 2 of the initial static exposure. The only data for motion conditions were for Low SS3 (4 subjects), Full SS3 (6 or 7 subjects), and Full SS5 (2 subjects); these motion data also were not significantly different for Days 1 and 2. Comparison of static and motion performance showed Low SS3 was slightly better than static, that there was virtually no difference between Full SS3 and static, and that Full SS5 was somewhat better than static. None of the subjects who undertook the Radar 2 task during any motion condition reported or showed evidence of motion sickness during any trial.

Cryptographic Decoding and Encoding

The cryptographic tasks were developed to measure motivation to perform routine work. Designed to be self-paced and operationally relevant, they involve near-field visual search and character recognition. For the decoding task, subjects were given a sealed envelope containing a coded message of 200 letters, arranged in two columns of 10-letter "words," and a decoding matrix. Decoding was accomplished by using each successive pair of message letters, from left to right, to enter the appropriate column and row of the decoding matrix in order to find the correct decoded character in the body of the matrix. The message was transcribed on a tablet page and sealed in an envelope along with the coded message and the matrix. Time to complete the decoding was recorded by the Test Administrator, with a 16 minute limit imposed. The encoding task was the reverse of the decoding one. Performance was scored as the mean minute-rate of transcribing the message in a single trial. Training was to a criterion of errorless performance in 15 minutes.

Examination of the differences between each subject's first run static scores and corresponding motion scores shows that there were no striking effects of motion on performance, except perhaps on Day 2 of

Full SS5, for encoding. In general, however, there were no systematic changes in mean performance levels with increasing motion severity or with time of exposure to motion. Two subjects performed the tasks while experiencing severe nausea. In spite of their condition, neither subject's transcription rate fell by more than three characters per minute in the motion condition, relative to his respective static score. These limited data suggest that performance of self-paced tasks requiring near-field visual search and character recognition would be little impaired for well individuals exposed to SES motions, except possibly after 24 hours of exposure to very severe motion (e.g., 40 kt., SS5). Sick individuals who are willing to work at such tasks seem to perform in a reasonably proficient manner (though this is not usually the case).

Navigational Plotting

The plotting task was closely modeled after the actual task performed by the Operations Specialist, acting as the plotter of radar returns on the bridge of U.S. Navy vessels. In many ways it was the most complex and realistic task of the test battery. It simultaneously tested several cognitive functions, including attention, perception, memory, and fine motor control under time pressure dictated by a rapid rate of information transmission. Subjects were required to plot own-ship's course and the periodically reported positions of radar contacts on a nautical map overlay. Twenty-nine contacts and one course change were presented in the 30-minute test. Each plotting record was scored to obtain the average distance error between plotted positions and corresponding "true" positions. Eighteen equally difficult versions of this task were available; no subject received the same version twice.

Training for each subject was continued until he satisfied the following criteria:

(1) Plotted own-ship's course within $\pm 10^{\circ}$ of the true course
(2) Plotted every report contact in the time allowed
(3) Plotted all contact positions within $\pm 10\%$ of their indicated position.

The effects of motion were evaluated from the difference scores measured between each subject's initial first- and second-day static tests and corresponding motion tests. The results are somewhat ambiguous. While it was true that no mean change in performance measured in any condition was statistically significant, several results suggested that task performance was sensitive to motion effects. There was a drop in performance proficiency in every case, from the first to the second exposure day. Moreover, both of the subjects who experienced motion sickness during the task failed to complete that assignment. On the basis of these limited data, one would have to conclude that

(1) individuals suffering from motion sickness cannot be expected to perform similar tasks with acceptable proficiency, and (2) performance effects due to other aspects of the motion are minor.

Visual Acuity Test

In this test, the subject was required to read aloud from textual material which was fixed to the cabin wall. He held his head at a constant distance from the wall, but his head was free to move vertically. The test was divided into 17 sequentially numbered sections with character size varied in distinct steps from one section to the next. At 36 inches, the visual angle subtended by the largest characters was 11.28 minutes of arc; the smallest was 2.82 minutes. Subjects read the section with the smallest legible character size and reported that section number to the Test Administrator, who determined reading accuracy from his copy of the text.

Analysis of motion effects was performed by comparing individual average static threshold values obtained in tests at the beginning and end of work periods on the first and second days of exposure, with comparable values measured during the different motion conditions. The data show that the mean change in visual angle was in the direction of increasing visual acuity threshold (i.e., larger character size required for correct reading) in every motion condition. However, the decrease in visual acuity was not large; mean changes never exceeded 0.7 minutes of arc. Results of statistical analysis indicate that the mean changes in threshold acuity were generally significant in all motion conditions more severe than Full SS3. However, the fact that no mean change was of particularly large amplitude indicates that no special provision need be made for the display of characters aboard a large-scale SES. Application of MIL-STD-1472A should be sufficient for ensuring the legibility of displayed characters in similar SES motion conditions.

ASSESSMENT OF SLEEP

Overall Considerations

In assessing habitability, a basic question is whether or not the environment allows individuals to obtain sleep that is adequate for the maintenance of health and effective performance. Any environment that significantly impairs the quantity or quality of sleep must be judged uninhabitable on a long-term basis. On the other hand, even environments that stress the working individual or impair his performance to a limited degree, may be habitable if sleep allows recovery from stress and fatigue.

Electrophysiological Recordings

In Phase II the attempt was made to record completely, on magnetic tape, electroencephalograms (EEGs), electrooculograms (EOGs), and electromyograms (EMGs) from all subjects, in every sleep period in both moving and static cabins, during every scheduled 48-hour mission. Prior to the beginning of each scheduled 48-hour run, the necessary electrodes were attached to that subject, of each pair, who was first to retire. Approximately 1-1/2 hours before the second subject was to retire, the Test Administrator entered the cabin and attached his electrodes, a procedure requiring a brief cessation of motion. Subjects were allowed to retire at times of their own choosing within a specified 1-1/2 hour period. When they retired, they connected the electrodes to a special "biopack" mounted on the cabin wall and were not disturbed by the Test Administrator until 3 minutes prior to scheduled arousal time. If a subject awakened before that time, he was allowed to disconnect the electrodes but remain in his bunk.

Twenty-one separate and complete sleep records, obtained from 11 subjects, were manually scored according to the method of Rechtschaffen and Koles (1968) to yield measures of time spent in each of the different sleep stages: S1, drowsiness; S2, light sleep; S3, S4, deep sleep, slow-wave sleep; and SREM, Rapid-Eye-Movement Sleep, when dreaming usually occurs. Periods of wakefulness (SA) were also scored according to this procedure.

The general composition of scored sleep, in both static and motion conditions, was slightly disturbed. While sleep period times were normal, they contained greater than normal percentages of S1 and SA time, and less than normal percentages of S3, S4, and SREM. Although the results indicated that the subjects may not have been fully acclimatized to the cabin environments and experimental protocol, they should not invalidate a static/motion comparison. A within-subject statistical test of data from seven subjects, in both motion and static conditions, suggested that sleep was unimpaired during exposure to moderately intense SES motion. Motion records were obtained primarily from variations of the SS3 condition, with the exception of one recorded from Full SS5. These limited results suggested that the sleep of subjects who were not at the time suffering from motion sickness was generally unaffected by motion. However, sickness did interfere with the sleep of some subjects: at least two individuals were apparently awakened by symptoms that developed during sleep. These observations imply that persons who succumb to motion sickness in the SES environment may be further afflicted with the inability to sleep.

Sleepiness Ratings

The Stanford Sleepiness Scale (SSS), comprising seven ordered response categories from "wide awake" to "lost struggle to remain awake," was administered repeatedly to the subjects during the long missions as a means of making quantified subjective comparisons of sleepiness between the static and motion conditions and between the day-sleeper and night-sleeper wake/sleep schedules. Each subject was asked to indicate his condition, in reference to the SSS, at approximately 4-hour intervals. The analysis of SSS scores was restricted to data collected from only 12 subjects (5 night-sleepers, 7 day-sleepers) who were able to complete at least one 24- to 48-hour exposure to any motion condition, and at least one 48-hour static condition. Individual SSS averages were grouped and averaged to yield time-of-day curves by schedule and condition.

Differences in mean SSS scores between schedules and conditions were evaluated by means of a three-factor analysis of variance, which showed that time of day was a significant factor but that there was no general effect of motion or of sleep schedule. The lack of any general motion effect must be interpreted cautiously due to the fact that the results were disproportionately weighted by the results obtained in SS3 conditions. Certainly, the possibility exists that an unbiased subject sample might have reported greater sleepiness in the more severe motion conditions if their sleep was disturbed by effects of motion. Since evidence of sleep disturbance was found for some subjects in the electrophysiological analysis, the results of the SSS rating analysis should be taken to indicate only that 24- to 48-hour exposure to the least severe motion conditions did not seem to produce unusual sleepiness in these subjects.

Circadian Rhythmicity of Oral Temperature

Because body temperature and sleep cycle are directly related, it was felt that the identification of disturbances in body temperature cycles, due to inversion of the wake/sleep cycle or due to motion, might aid in the assessment of sleep adequacy. To accomplish such identification, a thermistor circuit was placed upon the Test Administrator's console to serve as the oral ambient temperature indicator, and appropriate thermistor probes were placed in the moving and static cabins. Oral temperatures were measured for each subject at approximately 4-hour intervals, except during sleep periods. The subjects and the conditions of measurement were as described for SSS ratings.

All individual oral temperatures were averaged for each time of day by subjects, schedules, and conditions (combined motion vs static), and corrected for thermistor bias. Individual averages were grouped and averaged to give time-of-day curves by schedule and condition. Schedule means were not different within conditions, but the circadian cycles of oral temperature for the day- and night-sleepers were, as expected, 12 hours out of phase. Therefore, day-sleeper data points were lagged 12 hours for grouping with corresponding night-sleeper data. Finally, combined curves were generated for both motion and static conditions. A three-factor analysis of variance (schedules, conditions, and time of day) revealed only one significant difference: overall mean oral temperature was higher in the combined motion conditions than in the static condition (98.34°F vs 97.55°F).

The similar, normal, mean oral temperatures for both the day- and night-sleepers indicated no adverse metabolic effect of the inverted work/rest schedule upon the day-sleepers. Similarly, motion had no effect upon circadian variations of body temperature as compared to the static condition. The maintenance of a higher mean body temperature in the moving environment, however, suggests altered levels of metabolic heat production or altered mechanisms of heat conservation. Mean cabin temperature (regulated by the subjects themselves) apparently had no effect upon this situation. Greater metabolic heat production under motion may have been due to greater compensatory muscular activity. The amplitude of the oral temperature elevation, however, was quite small, indicating that such increased muscular effort would be easily tolerable.

ASSESSMENT OF STRESS

It is common practice to infer the experience of whole-body stress from urinary excretion rates of the catecholamine hormones adrenaline ($\dot{A}$) and noradrenaline ($\dot{N}A$). Almost any physical or psychological stressor can, if intense enough, elevate circulating catecholamines and their urinary excretion rates. Among demonstrated effective agents are pain, heat, sustained high acceleration or vibration, noise, exercise, confinement, many drugs, emotional stress, or even the demands of a difficult "mental" task. In view of this evidence, the approach taken in Phase II to estimate stress, due to motion or other factors, involved the assay of total urine output to determine $\dot{A}$ and $\dot{N}A$ excretion rates in all motion and static conditions.

Subjects were required to empty their bladders immediately before entering the cabins and thereafter to urinate into individually identified bottles. One waking and one sleeping sample was collected during each 24 hours of the longer runs; one 6-hour waking sample was collected from each subject during the shorter runs. When runs were aborted, each subject added whatever urine he could void to the current bottle, and the shortened time was noted for necessary adjustments in calculations. Aliquots (20 ml per sample) were withdrawn from the bottles and stored at -15°C for later analysis according to the method of O'Hanlon, Campuzons, and Hervath (1970).

Measures of $\dot{A}$ and $\dot{N}A$ were by far the most complete data obtained from this study. Nearly all waking and sleeping samples were obtained in every condition, including those from subjects experiencing motion sickness during the sampling period. Data from the long-mission static condition showed little evidence that mere confinement was an unduly stressful experience. Because subjects as a group showed little change in $\dot{A}$ or $\dot{N}A$ over repeated static runs, measures of each were averaged by subject, activity (wake or sleep), and days within runs to provide respective baseline control values. Measures from the motion conditions were then compared to respective static levels to yield difference scores.

$\dot{A}$ was found to be little affected by motion in all variations of SS3. However, in more severe conditions, $\dot{A}$ was generally elevated with respect to static levels. The difference for Medium SS4 was found to be statistically significant by t-Test; the differences approached significance for all other short mission conditions, i.e., Full SS4, and

Medium and Full SS5. The absence of generally elevated $\dot{A}$ levels during the long mission for Full SS5 was almost certainly due to the fact that it was undertaken by the most motion-tolerant subjects. Elevated levels of $\dot{A}$ were also found to be associated with the occurrence of motion sickness in 10 of 12 cases. The binomial, or "sign," test showed this association to be significant statistically.

For $\dot{NA}$, no difference between static and motion excretion rates was found to be significant, and there was no significant association between elevation of $\dot{NA}$ and the occurrence of motion sickness.

A final descriptive analysis was performed using the absolute values of $\dot{A}$ and $\dot{NA}$ measured in different motion conditions. To determine whether the experience of stress was more closely related to acceleration within the critical motion-sickness bands (0.1 to 0.5 Hz) than to overall acceleration, mean "awake" excretion rates for $\dot{A}$ and $\dot{NA}$ were calculated across subjects and by conditions. Progressive increases in rates were found for both catecholamines with increasing acceleration. To further illustrate this motion effect, individual tot 1 catecholamine rates were averaged and plotted in Figure 8 as a function of rms heave acceleration within the 0.1 to 0.5 Hz band. For SS3, mean levels approximated the average static level, but for acceleration greater than about 0.10 rms g, acceleration was associated with progressively higher rates up to a maximum level about 38 percent above the average static level.

The implications of these results are that it is desirable to limit long-term SES operational motion conditions to heave acceleration levels on the order of the Full SS3 condition studied here; that motion-tolerant individuals should be selected as crew members; or, assuming adaptation reduces stress, that crew members should be adapted to the expected motion before duty on the SES.

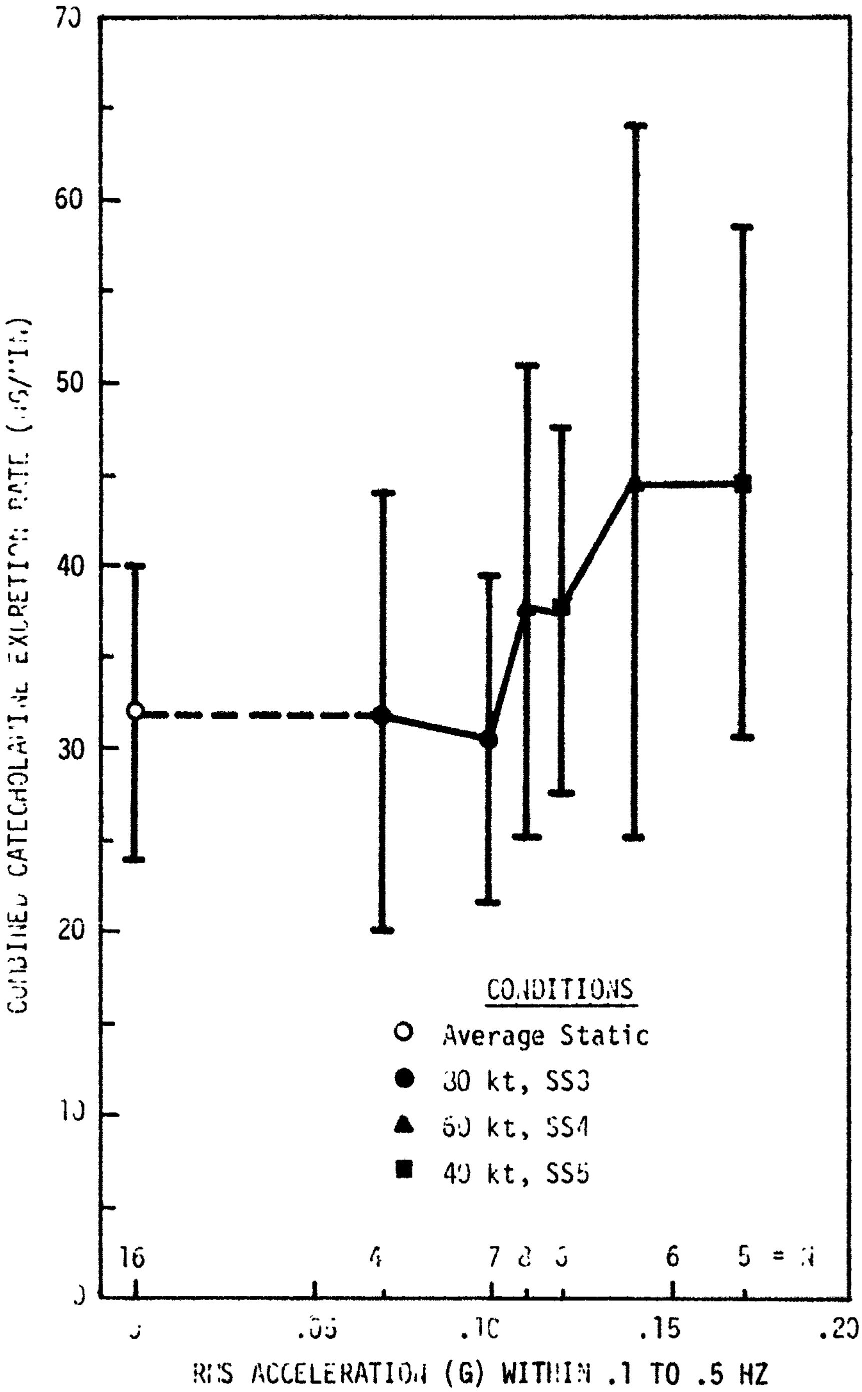


Figure 8 Total catecholamine excretion rate (M±SD) as a function of rms acceleration within the .1 to .5 Hz frequency band for various conditions of motion. (Fig. 24, Vol. 4)

CLINICAL MEDICAL EFFECTS

Emesis is generally considered to be the most severe stage of kinetosis, but there are many other important and severe symptoms which may be more disabling than vomiting in individual cases. Most of the subjects in Phase II displayed a wide variety of kinetosis symptoms. Most of those who aborted runs did so after vomiting, but three subjects who aborted without vomiting were suffering severe kinetosis as evident from other symptoms.

The response to vomiting and the symptoms associated with vomiting varied from subject to subject, but the constellation of associated symptoms includes: lassitude, anorexia, dizziness, headache, and intermittent nausea usually temporarily relieved by vomiting. Certain features of the kinetosis syndrome were common to all:

1. During runs planned for more than 2 hours duration, a subject who once vomited continued to vomit or have other symptoms of kinetosis until he aborted the run.

2. A subject who vomited, or was in the prodromal stages of vomiting or was attempting to alleviate the feelings of motion sickness, would sooner or later abandon his scheduled performance tasks.

3. Cessation of the motion relieved the symptoms in all cases, with time for complete alleviation varying from a few minutes to 12 hours in individual cases. However, with one exception (who induced vomiting in himself), no subject vomited after the motion was stopped. No medical treatment was administered by the physicians with the exception of aspirin for headache.

The most severe case of repeated vomiting was shown by a subject who vomited 10 times within about 23 hours before he aborted the run. He recovered promptly and completely without treatment. Another subject, who vomited 6 times in about 2-1/2 hours before aborting, was the only case in which prior medical condition (gastroenteritis) may have reduced his tolerance to motion sickness.

The overall incidence of emesis is summarized in Table VII, and the overall incidence of abort in Table VIII. It should be noted

TABLE VII

The ratio and percentage of the volunteers† who vomited at some time during the condition (Fig. 7, Vol. 5)

Condition	July	August	September	TOTALS
SS3*	2/7**	1/5	1/6	4/18=22%
SS4*	3/5	0/0	5/8	8/13=62%
SS5*	0/0	3/6	5/7	8/11**=73%
0.3 Hz 0.19G	0/0	3/5	0/0	3/5=60%

* Refers to any amplitude level within the condition, ranging from 64% to 100% of the heave acceleration.

** Although the monthly totals in SS5 are correct, two individuals were re-exposed to SS5 in September, for a total of only 11 individuals.

TABLE VIII

The ratio and percentage of the volunteers† who aborted with or without vomiting by conditions (Fig. 8, Vol. 5)

Condition	July	August	September	TOTALS
SS3*	4/7	1/5	1/6	6/18=33%
SS4*	3/5	0/0	5/8	8/13=62%
SS5*	0/0	4/6	5/7	9/11**=82%
0.3 Hz 0.19G	0/0	3/5	0/0	3/5=60%

* Refers to any amplitude level within the condition, ranging from 64% to 100%.

** Although the monthly totals in SS5 are correct, two individuals were re-exposed to SS5 in September, for a total of only 11 individuals.

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† Ratios and percentages based on number of volunteers, as opposed to number of runs. See note on pp. 45 and 47.

that incidence is reported by motion condition regardless of attenuation or the number of runs a subject experienced at each condition. Partitioning incidence by sea state and attenuation would result in too few subjects in different conditions to formulate meaningful percentages. Therefore, if unattenuated sea state motions were used in all conditions, higher percentages of mission aborts may have resulted. (The sine wave condition shown in the table was used at a time when the sea state motion was not available.)

The complex and specialized nature of the SES model and the major sources of variation suspected to affect the emesis and voluntary abort percentages preclude generalization of these results to other motion conditions of a different vehicle, time duration, activity cycles, or adaptation state.

The standard score of vestibular function testing used during the selection process for the subjects of Phase II was only marginally related to susceptibility to heave-induced motion sickness and therefore is an unreliable predictor in its current form.

There are five general approaches to the problem of limiting the incidence of kinetosis on operational naval vehicles. These are:

1. Crew selection of personnel who are resistent to motion sickness.

2. Preventive treatment for kinetosis.

3. Adaptation (habituation) of crew to motion condition.

4. Modification of motion experienced by the crew through engineering design.

5. Limitation of operation of the vehicle during the more severe sea states.

COMMENTS AND RECOMMENDATIONS

During Phase II of the SES habitability simulations, the upgraded ONR/HFR Motion Generator provided motions representative of those calculated for a generic 2000-ton SES without ride control at three tested sea state/ship speed/heading conditions, accurately reproducing the heave motions which dominate these conditions with great fidelity over their respective range of interest; i.e., roughly 0.16 to 1.6 Hz.

By far the dominant problem for the relatively inexperienced crewmen involved in Phase II was motion sickness (kinetosis), which afflicted a majority of them at one condition or another. The ability to perform routine, prolonged mental work was severely degraded in individuals suffering from kinetosis. The full extent of that degradation could not be determined due to the unwillingness or inability of those individuals to accomplish assigned tasks or even to remain in the motion environment. There are critical implications of these data for operational use of all seaborne platforms with similar or worse motion profiles.

At the lowest motion condition tested (Low SS3, wherein $\sigma_{g_z} = 0.13g$ and $\sigma_{MSI} = 0.021g$) there was little kinetosis. At a range of intermediate conditions, including Medium and Full SS3 and Low and Medium SS4, a large fraction (from 1/3 to 1/2) of the crewmen experienced severe nausea or emesis, but there was no systematic pattern among these conditions. A few subjects proved sufficiently kinetosis-resistant to take Full SS5 without emesis for short periods of exposure, and two of these completed a 48-hour run. Thus, these data emphasize the idiosyncratic nature of motion sickness.

The conditions causing appreciable kinetosis in these inexperienced subjects were characterized by rms g_z from 0.19 to 0.28, with σ_{MSI} from 0.05 to 0.13g. Attenuation of the motions in the frequency range of 0.1 to 0.6 Hz, so as to reduce σ_{MSI} to below 0.025g, would seem to reduce most of the kinetosis problems; however, the data from this study are insufficient to prove this conclusion. Based on these data, application of a Ride Control System or improvement of ride quality compared to that of the tested 2000-ton model is recommended.

At all conditions for which sufficient data were obtained (except for Low SS3), there were appreciable decrements in visual motor-task performance which are on the borderline of operational significance (e.g., 50+ percent increases in missile-tracking error and lock-opening times, 30 percent reduction in ECM tracking bandwidth, 20+ percent increases in keyboard operations and maintenance times); however, these decrements seldom achieved statistical significance because they are comparable to the inter-subject variations due to skill and learning.

There was not as much covariation of either visual-motor-task performance or motion ratings with increasingly rougher sea conditions as was experienced in Phase I and IA of this study series. There was repeated evidence that performance started to deteriorate near the Low SS3 condition ($\sigma_{g_z} = 0.13g$), with decrements remaining roughly constant thereafter for the other conditions up to Full SS5. Despite the data from the two kinetosis-resistant subjects, showing gradually improving visual motor performance at SS5, both debriefing comments and observations on the subjects during experimental runs suggest that typical performance decrements would start to get worse beyond $\sigma_{g_z} = 0.20 - 0.25g$. Runs by more typical and sea-experienced crewmen are needed to check this suspicion.

Crewmen compensated for motion interference in visual-motor tasks by increased mental and physical effort, as evidenced (weakly) by their responses to habitability questions. Better methods for quantifying and logging this compensatory effort must be employed in future simulations.

In many cases the best performance on visual-motor tasks under static conditions proved to be the most resistant to performance impairment by severe motion. This observation has important implications for SES crew selection, training, and roughwater operating procedures; and it deserves careful investigation in future SES simulations or operational tests.

Higher-order cognitive functions, such as attention, visual pattern recognition, and memory, were not impaired in individuals exposed for periods of up to 48 hours to any of the motions studied, so long as they did not suffer from motion sickness.

Near-field visual acuity was slightly impaired by all motions employed in Phase II; however, characters subtending at least 5.0 arc-minutes visual angle (critical element size of about 1.0 arc-minutes for standard visual acuity target "F") should be legible for normal reading distances in similar motion environments.

The quantity and quality of sleep obtained in motion was impaired for some individuals who apparently developed symptoms of kinetosis during sleep. When sickness did not occur, individuals seemed to sleep normally, at least during variations of SS3 motion.

"Stress" hormone excretion rates were generally elevated during exposures to variations of SS4 and SS5. Individual differences were large, indicating widely different tolerances for stressful motion effects. On the average, there appeared to be a monotonic relationship between stress and heave acceleration imparted in the 0.1 to 0.5 Hz frequency range.

The subjects for Phase II were U.S. Navy enlisted personnel with little or no previous sea experience, whereas the eventual crew of the operational SES will be experienced seamen. It is extremely difficult to generalize about experienced SES personnel from data obtained from subjects unadapted to sea motion.

As discussed in Appendix A there are a number of generic motion issues that have not been addressed by this report: the existance of "equivalent doses" of motion exposure, the existance of a motion sickness response function, whether a superposition principal applies to motion effects, whether response is nonlinear, the presence of saturation effects, the ability to specify motion in terms of temporal or spectral response only, and the effects of adaptation. The conclusions in this report thus apply only to those motions actually simulated and can only be extrapolated to SES with similar motion profiles. Motion guidelines expressed in the Appendix are not applicable to other ships with different motion profiles. It is thus strongly recommended that fundamental studies addressing these issues be continued. It is further judged that a "High Fidelity" simulator with the capability of reproducing complex motion provides an excellent instrument for conducting these studies.

APPENDIX A

SECONDARY OBJECTIVES

General Background

At the onset of the SES development it was recognized that the SES, along with other advanced ship concepts, represented a major departure from past ship designs in that a means other than hull form alone was available for controlling ship motion. The SES thus presented a chance for a genuine improvement in seakeeping qualities. The fact that the SES design was being pursued as an individual development project rather than a general industry wide design evolution also indicated a need for caution since a significant expenditure of government R&D resources was at stake. Thus, almost from its inception, the project took an interest in habitability and human performance and the application of such factors to engineering evaluations in proposed designs. It was highly desirable that ship motions could be predicted in advance for each design and that the acceptability of those motions relative to those of another ship could be evaluated. As it turned out, this approach would later become especially important in evaluating the performance or even the need for the SES Ride Control System (RCS), a subsystem of the SES lift system with the capability of controlling the amplitude of ship motion in both the spectral and temporal planes.

Early literature searches (Refs. 1 and 2) indicated a fundamental lack of physiological data suitable for the analytical comparison of the effects of ship motion, especially motions representative of high speed ships. Existing motion criteria, such as ISO Standard 2631, "Guide for the Evaluation of Human Exposure to Whole-Body Vibration", and MIL-STD-1472 (Fig. A-1), provided criteria for exposure to motion in terms of the spectral content of the motion. Ideally these criteria are applicable only to single-frequency sinusoidal motions, although the criteria are often extrapolated to more general cases. In addition, these criteria did not extend to frequencies below 1 Hz.

Temporal criteria were available in two forms: Criteria for impulsive motion had been under investigation for some time (Ref. 3), but such motion was outside the regime of the SES, i.e., low impulses which continued over long periods. (In fact, the cases of extreme

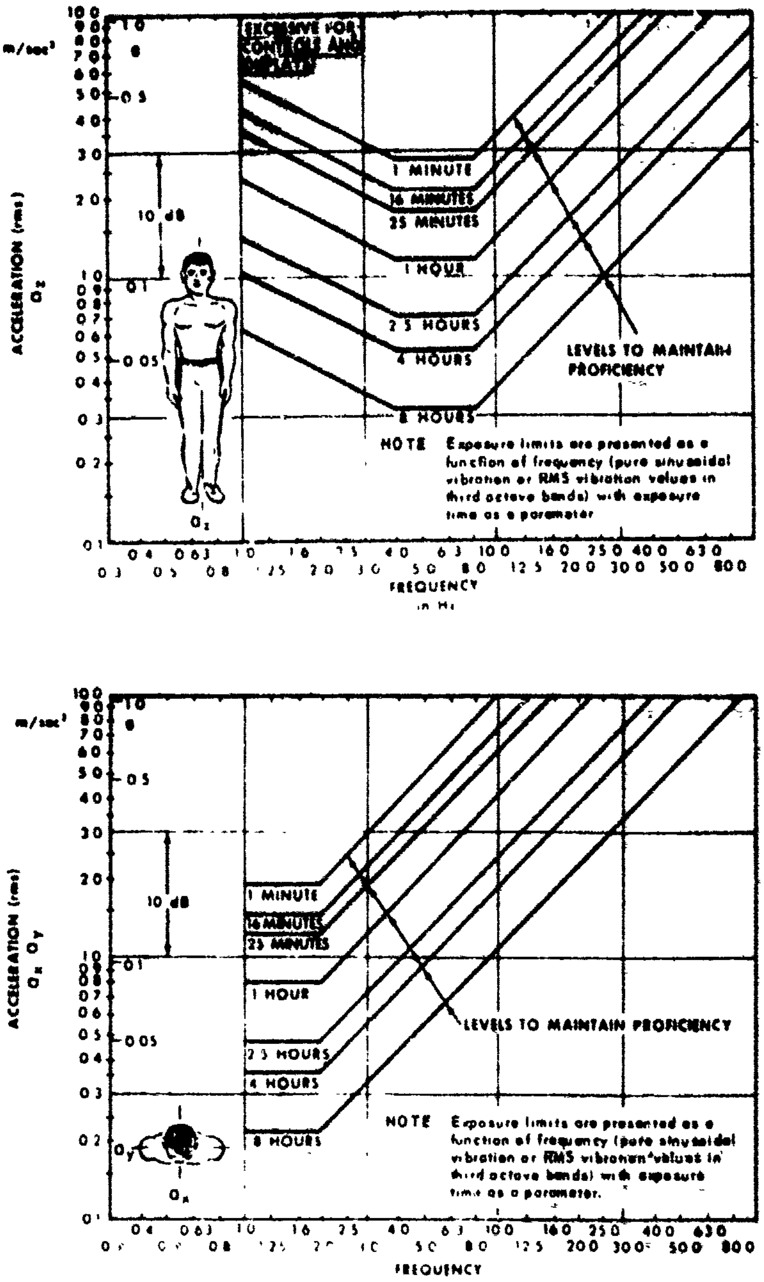

Figure A-1. Vibration Exposure Criteria for Longitudinal (Upper Curve) and Transverse (Lower Curve) Directions with Respect to Body Axis (from MIL 1472).

motions predicted for some early SES designs were closer to aircraft motions (Ref. 4), which were later addressed in MIL-F-9490D (USAF) for flight control systems.) Temporal standards for time limits of exposure (Refs. 5, 6 and 7) were based on relatively short term exposure data (Fig. A-2) or, at the other extreme, for very long term exposure as deduced from fragmented insurance data on occupational hazards.

Data on the spectral region below 1 Hz was primarily in the form of sickness studies (Refs. 8 and 9), although various studies had been conducted in "zero g" and centrifuge tests. Wendt and his co-workers performed a series of studies involving exposures to intense motion for periods of the order of 15 minutes. Emesis was typically induced during this period. The wave form of exposure was generally a best effort to generate a rectangular wave in either displacement, velocity, or acceleration, using available equipment (i.e., a commercial grade elevator). Later work by O'Hanlon and co-workers still used an elevator but now included pitch and roll gimbals and more sophisticated instrumentation. This effort dealt primarily with exposure times of two hours and sinusoidal motion. As a result of this work, a mapping (Fig. A-3) was constructed indicating the cumulative percentage of people experiencing frank emesis in a given exposure period as a function of frequency and acceleration amplitude. This latter work was still being analyzed at the time the Goleta work was underway.

As a result of these circumstances, it was deemed necessary to gain a "familiarization with the effects of SES-like motions on crew performance and habitability by first hand experience". A plan was established in which motions predicted for various designs would be simulated, performance and other factors measured, and results verified or at least the validity of the simulations tested by further simulations using measured ship motion from available SES test craft. This plan was implemented resulting in an initial report (Ref. 10). This report presented the results of 6 degree-of-freedom (DOF) simulations at Marshall Space Flight Center (MSFC) where both motions aboard a 100-ton SES test craft and motions predicted for an early 2000-ton SES design were simulated. The MSFC simulator provided good high frequency 6 DOF response but limited travel in heave. Since primary concern at that time was centered around the high frequency aspects of high speed ship motion, a decision was made to "live-with" those limitations and a best effort at simulating 6 DOF SES motions was made. These tests indicated that (within the then current knowledge and test refinement) the predominant motion of the SES (pitch, roll, and heave) dominated all other aspects of the simulation and that it was indeed more important to simulate the full heave of a large SES than all of its 6 DOF. Accordingly, simulations were moved to a 3 DOF (pitch, roll, and heave) simulator then located at the Human Factors Research, Inc., facility at Goleta, California. Although the heave response of this simulator

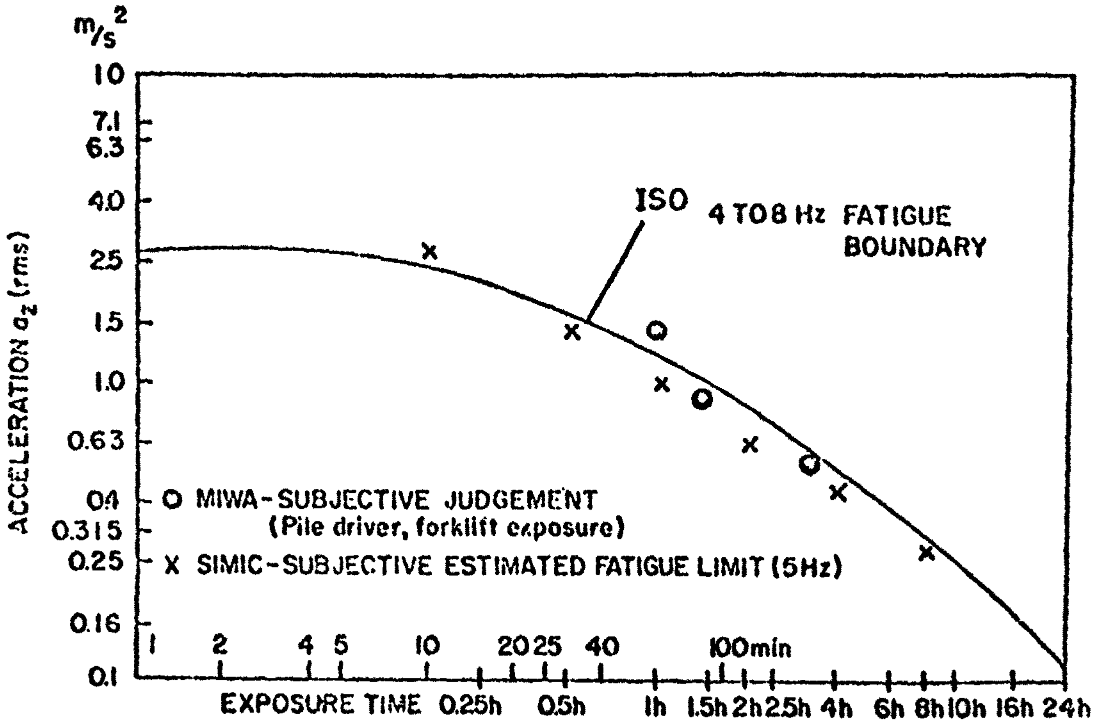

Figure A-2. Allowable Acceleration as a Function of Time of Exposure. Experimental Points Compare Subjective Judgement of Equal Failure to ISO Standard Curve.

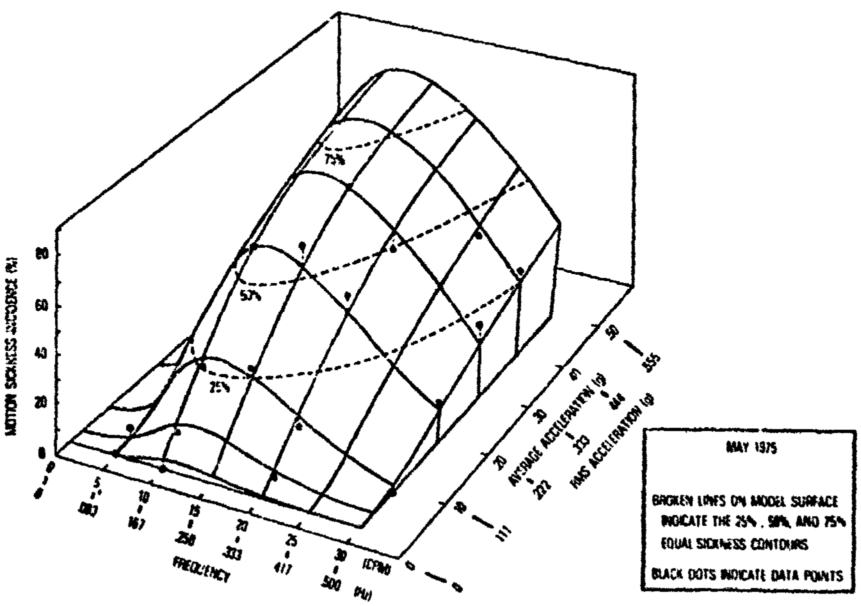

Figure A-3. An Empirically Derived Model of Motion Sickness in Terms of Frequency of Excitation and Acceleration Amplitude.

allowed sufficient travel to simulate SES motions, the system's frequency response was insufficient to faithfully reproduce those frequencies present in the more complex waveforms representative of actual SES motions. The simulations were accordingly conducted in two phases: an initial phase (Refs. 11 and 12) prior to the total modification of the simulator, and a final phase reported in these volumes following full modification of the simulator.

Secondary Issues

It was recognized from the outset that available sample size and resources were insufficient to allow definitive standards to be developed, and although the program has realized its fundamental objective of gaining first hand experience with SES-like motion, several secondary issues with respect to application of motion data in engineering design decisions still remain.

1. Equivalent Doses

One of these issues was the existance of an "equivalent dose" of motion. Ideally one would like to envision a ship operating in a given sea state. The probability of that sea state could be estimated based on empirical facts, the response of a given ship in that sea state could be calculated, and the relative occurrence of that motion condition could be estimated. Based on established human response data the importance of these conditions in the life of a ship could be estimated and a statistically-based engineering decision could be made as to the merit of the particular design, much as we currently do with structural design criteria. The implication of this logic is that certain integrals of the motion variables over time exist which definitize a quantity or "dose" of motion, that it will be possible to quantify crew performance and habitability variables in terms of this dose, and that it will be possible to relate the effects of doses with different spectral and temporal content. It also implicitly recognizes the fact that the spectral or temporal content of the motions may be adjusted, but the motions not eliminated entirely. The ability to predict in advance the resultant effects of motion exposure thus seems to depend on the existance of a given "equivalent motion dose", a desirable but not necessarily true condition.

2. Motion Sickness Response Function, Superposition, Non-Linear Response

The data presented in Figure A-3 indicate that, at least for single-frequency sinusoidal motion, the incidence of motion sickness is a function of only the time of exposure, the acceleration amplitude, and the frequency of the motion. This relationship is described in terms of a variable, MSI (Motion Sickness Incidence), which gives the cumulative percentage of frank emesis expected from young unadapted adult males within two hours after initial exposure to motion (Ref. 9). This is described in terms of the asymptotic proportion of sick individuals, P_A, and the time dependent proportion, P_T, as

$$MSI = 100\ P_A P_T$$

$$\text{where } P_j = \frac{1}{\sigma_j\sqrt{2\pi}} \int_{-\infty}^{X_j} \exp\left[\frac{-(X_j-\mu_j)^2}{2\sigma_j^2}\right] dX$$

$$j = A,T$$

$$\mu_A = -0.80 + 2.73 \log^2 (f/f_p)$$

$\mu_T = 2.00 - P_A$ $\qquad$ X_A = common logarithm of acceleration (RMS g's)

$\sigma_A = 0.46$ $\qquad$ X_T = common logarithm of time (minutes)

$\sigma_T = 0.36$ $\qquad$ f = frequency (hertz)

f_p = 0.17 hertz

If the differential of MSI is set equal to zero, it can be shown that this formulation predicts the existance of a single frequency, f_p, at which personnel are most sensitive to motion regardless of acceleration amplitude and that iso-emesis contours are described by the condition:

$$W(f) = \frac{a}{a_p\ (MSI)} = 10^{-2.73 \log^2 (f/f_p)}$$

where a_p (MSI) is the acceleration level required to produce a given MSI at frequency f_p. This relationship is depicted in Figure A-4. It was originally hoped that this expression would provide a transformation or weighting variable which could generate a frequency independent acceleration variable which could be used to determine MSI in more general cases. (This was based on the desire to have such a function rather than any deductive reasoning which indicated that such a function should exist.) Thus, just as the luminous response curve relates radiant watts to radiant lumens, the motion response curve would relate experimental acceleration to effective acceleration (Ref. 13). It was hoped that this dependence could be carried over to a more general case: If the heave acceleration, $\ddot{z}$, could be decomposed into sine waves:

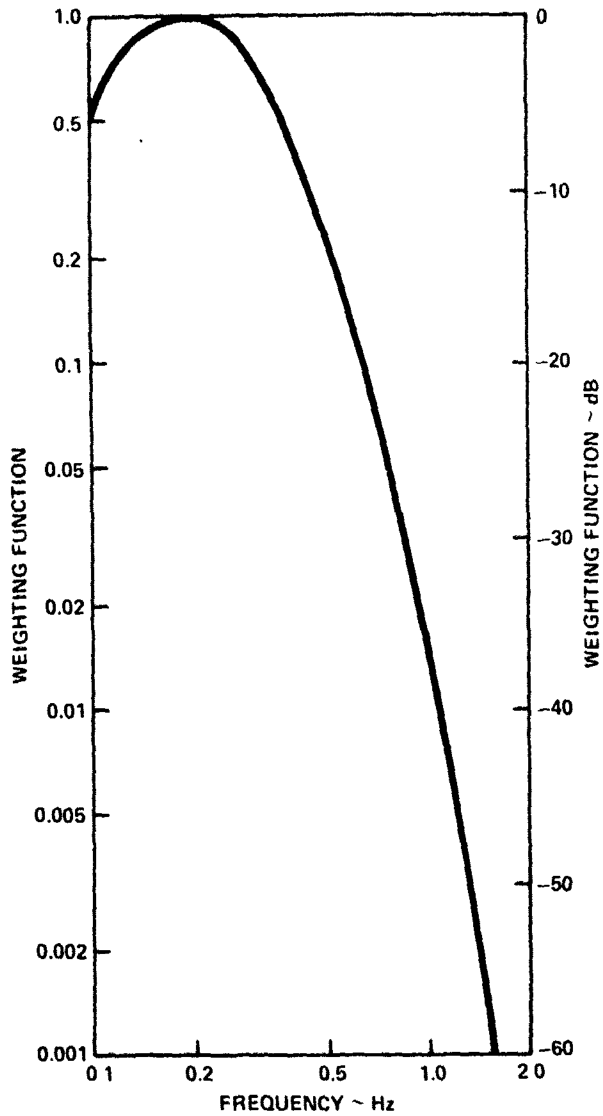

Figure A-4. Contour of Constant MSI as a Function of Frequency. The Acceleration Transformation Which Provides a Frequency Independent Variable for Computing MSI.

$$\ddot{z}(t) = \Sigma\, A_i(f_i) \sin [2\pi f_i t + \beta(t)]$$

it would be possible to generate an effective acceleration (in terms of predicting MSI):

$$\ddot{z}_e(t) = \int \ddot{z}(t)\, W(f)\, df$$

which would in turn allow the specification of some "dosage" for motion sickness in terms of a yet to be established function of the variable $\ddot{z}_e$:

$$Y = \frac{1}{T} \int_o^T F\,(\ddot{z}_e)\, dt.$$

If such a relationship exists we have not been able to definitively establish its existance. The primary effort has been to use a root-mean square (rms) effective heave acceleration defined by:

$$\sigma^2_{MSI} = \int [W(f)A(f)]^2\, df$$

where A(f) are the Fourier amplitudes of the acceleration.

This expression is substituted directly for the single-frequency acceleration term of the MSI integral. The approach has been used unsuccessfully in unpublished analysis of Wendt's data, data from our own simulations, and the data of Guignard and McCauley (Ref. 14). This may be due to an unsound hypothesis or to a variety of other reasons. Again, in analogy to the optical response curve, a series of yet to be understood phenomena analogues to brightness, color saturation, etc., may be present. Also, the response may be totally non-linear. A series of cross-coupling effects by which motions interact has been postulated by various investigators. As will be discussed elsewhere, such a finding would not be at odds with the current MSI formulation. A series of basic tests as initiated in Reference 14 need to be carried forth to determine if a superposition principal can be applied to sickness-inducing motions.

Temporal and Spectral Criteria

As indicated previously, motion criteria may be described in terms of either time or frequency domain principals. Criteria developed using single-frequency sine waves can be reasonably precise and are easy to apply in practice. Ship motions whose spectra include only one or two sine wave components are common; however, when the speed of the ship increases, the nature of the motion changes (Refs. 15 and 16). The bandwidth of the motion increases dramatically and the center of frequency of the encounter motion also increases. Accompanying this increase in bandwidth is a finite probability that spectral components can at some time become exactly in phase resulting in an impulsive motion, i.e., those motions whose crest factor (ratio of peak acceleration amplitude to rms value) is large. In the extreme case (a delta function response), all frequencies would be present and the motion would obviously be unacceptable. This was recognized immediately (Ref. 17) as an impediment to utilizing frequency criteria for ship evaluation as well as for many other transportation modes. An additional difficulty with the application of single-frequency criteria is that even in those instances when only a few spectral elements are present, the presence of certain combinations of spectra may exacerbate problems. This is especially true with respect to certain single-frequency criteria now being considered for sea sickness. Although kinetosis is a narrow band phenomena, and although the manner in which broad band accelerations contribute to kinetosis is not quantitatively understood, ample evidence exists to indicate that the presence of more than one spectral element can significantly increase MSI.

At the other extreme is the application of temporal criteria. When impulsive motion is large, criteria can be definitive. As impulse amplitude decreases, application becomes more difficult. In the extreme instance of very small amplitudes, it becomes necessary to test for long periods of time to establish the suitability of such motion. This fact led to the adoption of 48-hour test periods for the Goleta simulations. It was the intent that the first 24 hours would be a "settling out" period, though in fact, sea sickness precluded "settling out" for most of the tests.

Criteria Used in Evaluating Performance and Habitability in Various SES Designs

As indicated in the foregoing, a number of problems still exist within the framework of existing and proposed criteria. Certainly the data developed under this effort have been insufficient to propose new motion standards and much fundamental work remains to be done. It has been possible to develop certain "common sense" and empirical procedures for evaluating SES motions and it should be possible to develop similar procedures for other ship types.

Before proceeding with a description of the SES procedures, it should be first noted that a Pierson-Moskowitz distribution is used for modeling sea states within the SES project. Other models might also be used, but in general, such models of fully developed sea states lead to ship motions with specific statistical distributions. (The distribution may be Rayleigh or other. Although the volumes in this report compare SES heave acceleration distributions to the normal distribution, SES motions are better described by a Weibull distribution as long as extreme values are not considered. Heave amplitudes are bounded on one side by one g, free fall, and are relatively unbounded on the other due to slamming.) The rms value can thus be related directly to the peak value provided the distribution is known. (Interestingly, the percentage of amplitudes exceeding 3σ is relatively insensitive to the distribution for several distributions.) A special treatment will be required for sea states which are not fully developed. Such sea states however generally imply reduced motions.

With these facts in mind two "rule of thumb" procedures for evaluating SES motions have been developed. These procedures are based on both spectral and temporal domain experience gained in SES test craft, SES simulations and in literature searches.

The first and prime "rule-of-thumb" is based on rms acceleration. Simply stated, this rule relates the probability of an acceptable ride to the rms heave acceleration at a given point on the ship. Table A-I indicates the range of values. The preferred 0.1 g ride allows infrequent impulses corresponding to 3σ values of 0.3 g. The less preferred 0.2 g rides allows 3σ impulses of 0.6 g. In evaluating these limits one can compare a "common sense" value for the limit of ride acceptability to a 3σ value of 1 g, corresponding to a ride limit of 0.33 g.

This rule-of-thumb is particularly convenient. It is a single number that quantifies the ships operating conditions. In an operational situation an rms meter can readily measure the rms g, and such meters have indeed been used onboard SES test craft in gathering ride data.

More general analysis is also applied. In the frequency planes, motions are evaluated according to criteria similar to that indicated in Figure A-5 (Ref. 16). The frequency band is divided into three general regions: The "Whole Body" region with frequency greater than or approximately equal to 1 Hz, a relatively benign transition region with frequency between 0.7 and 2 Hz, and a Sea Sickness region with frequency less than 0.7 Hz. Similar curves, often with stylized variations, have been under consideration for some time in proposed motion standards. The region above 1 Hz is adapted from ISO Standard 2631. Different curves describe different levels of Fatigue-Decreased-

TABLE A-I

SES Local Heave Acceleration Criteria.
First Rule-of-Thumb for SES

Confidence of an Acceptable Ride	Standard Deviation of Local Vertical Acceleration, g
High	$\sigma \leq 0.1$
Moderate	$\sigma \simeq 0.15$
Marginal	$\sigma \geq 0.2$

TABLE A-II

SES Local Heave Acceleration Criteria
in Terms of Motion Sickness Weighted Heave
Acceleration Variable, σ_{MSI}.
Second Rule-of-Thumb for SES

Confidence of Acceptable Ride	σ_{MSI} (weighted rms g)
High	$\sigma_{MSI} \leq 0.025$
Moderate	$\sigma_{MSI} \geq 0.04$

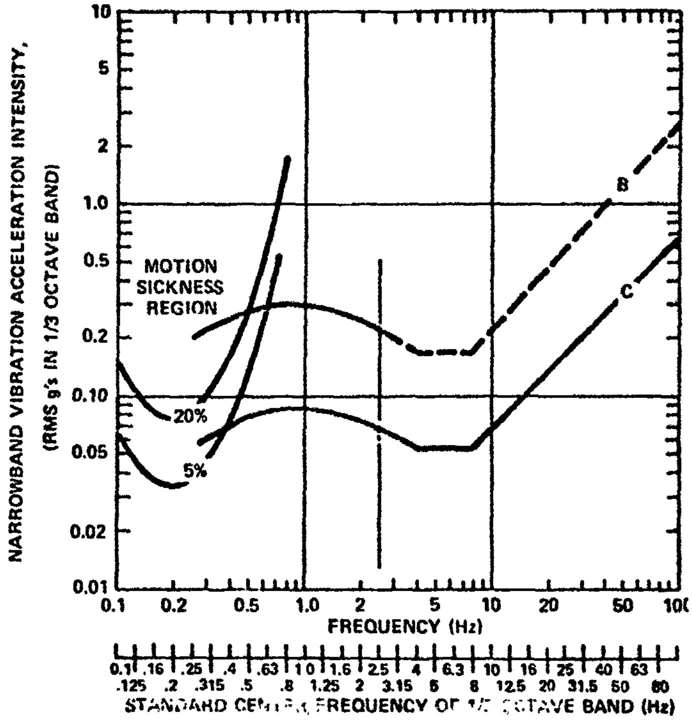

Figure A-5. Frequency Domain Criteria Consisting of Three General Regions: The Whole Body (f > 1 Hz), a Relatively Benign Transition Region (0.7 < f < 2 Hz), and the Sea Sickness Region (f < 0.7 Hz).

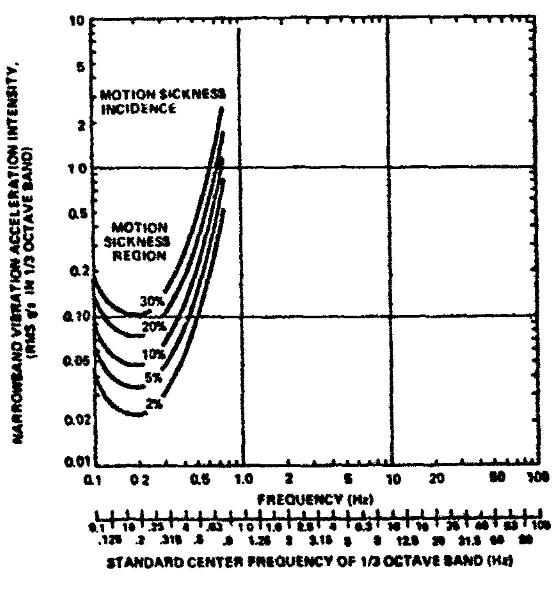

Figure A-6. MSI as a Function of Frequency and Acceleration (for Unadapted Male Subjects).

Proficiency as described therein. The motion sickness region is defined in terms of O'Hanlon's data (Fig. A-6) for cumulative emesis of unadapted males within a two hour period. Different curves indicate different acceptable levels of MSI. The intermediate region represents "best joining" of the two phenomena using curves adapted from Shoenberger's equal sensation contours (Ref. 18).

In each case computed or measured SES vertical acceleration spectra resulting from combined 6 DOF motion is compared to these criteria on a one-third octave basis. The Whole Body region is interpreted according to general ISO practice for each band. These procedures tend to reinforce the first "rule-of-thumb". A procedure to be used in evaluating the transition region has not yet been established.

In the Sea Sickness region, a particular value of MSI, typically 5 to 20 percent, is chosen based on operational considerations. In the past, various arguments have been presented to the effect that Navy crews would be "adapted" or "naturally selected" and that use of such MSI curves would be overly conservative. In the case of a conventional ship setting dead in the water, such judgement would seem to be well founded. Measured data indicate such ships often generate almost sinusoidal motion at the peak sea sickness frequency, 0.17 Hz. A "rough ride" criteria of 0.1 g rms is sometimes used for such ships. Similar spectra can also occur on air cushioned vehicles. Measurements on the SRN-4 hovercraft indicates that conditions in the English Channel are at times approximated by two-sine-wave seas. However, in more fully developed seas, several one-third octave bands of the sea sickness region will be filled. The effects of the different bands are definitely cumulative, and use of the above criteria without consideration of other bands is definitely not conservative. Reference 11 recommended no more than 0.05 g rms total within the sea sickness band. Based on these considerations, our test results, and literature review a second rule-of-thumb has been established for evaluation of SES ride quality in the sea sickness region. This is given in terms of the weighted rms acceleration described earlier. Even though "weighted acceleration" has been unsuccessful in predicting MSI in a quantitative manner, the second rule-of-thumb indicated in Table A-II has been used for evaluating broad-band SES motions in terms of an acceptable level of motion sickness. Thus, the preferred ride would have a motion sickness weighted heave acceleration less than 0.025 g. This would typically correspond to a local heave acceleration of 0.1 to 0.15 g rms.

Comparison of Tested Motion to Other Ship Data

Figures A-7 through A-11 taken from various "rough ride" conditions, are included for comparison to some of the motions that have been simulated.

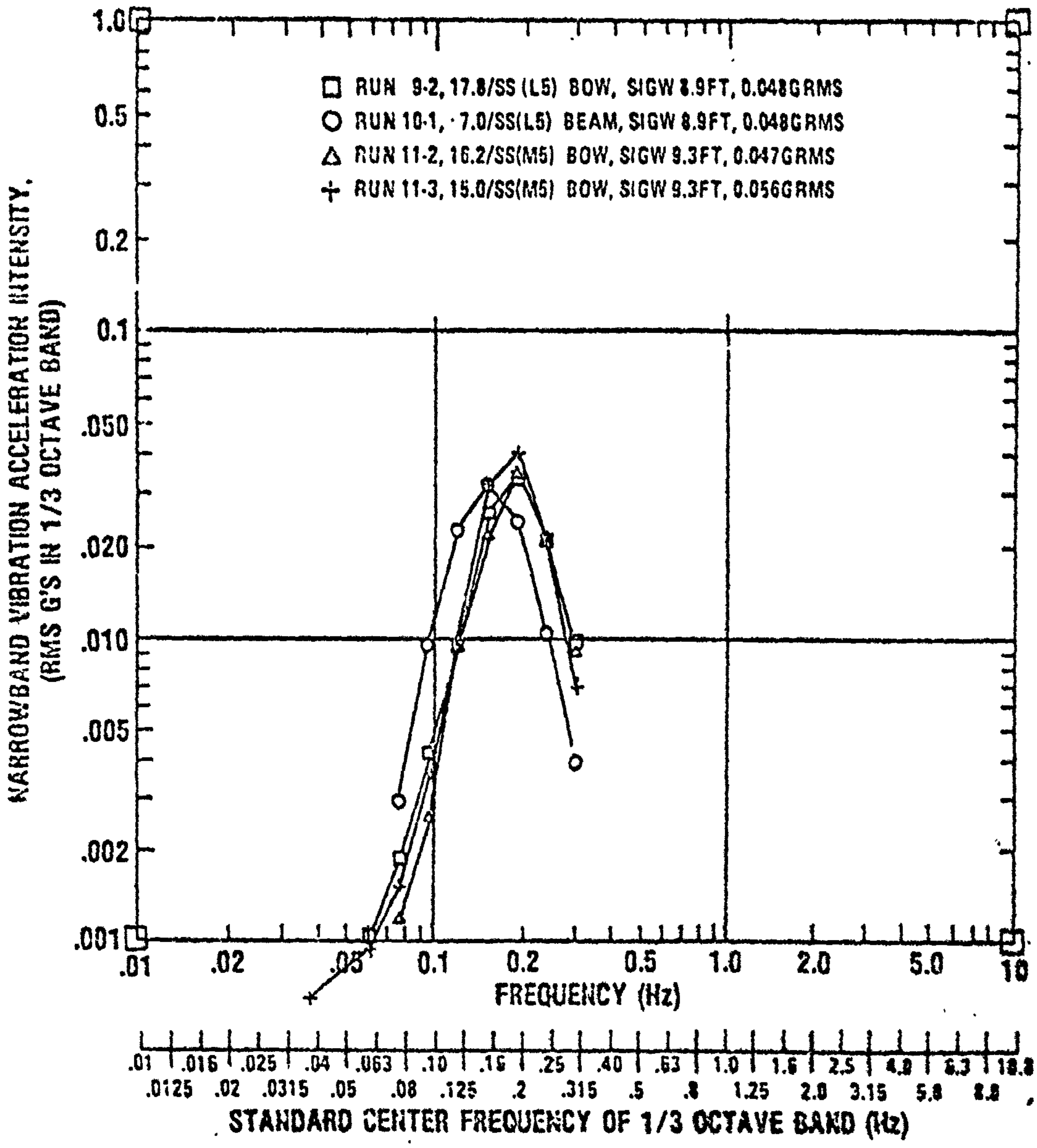

Figure A-7. Measured Motion Spectra for a 1052-Class Destroyer Escort.

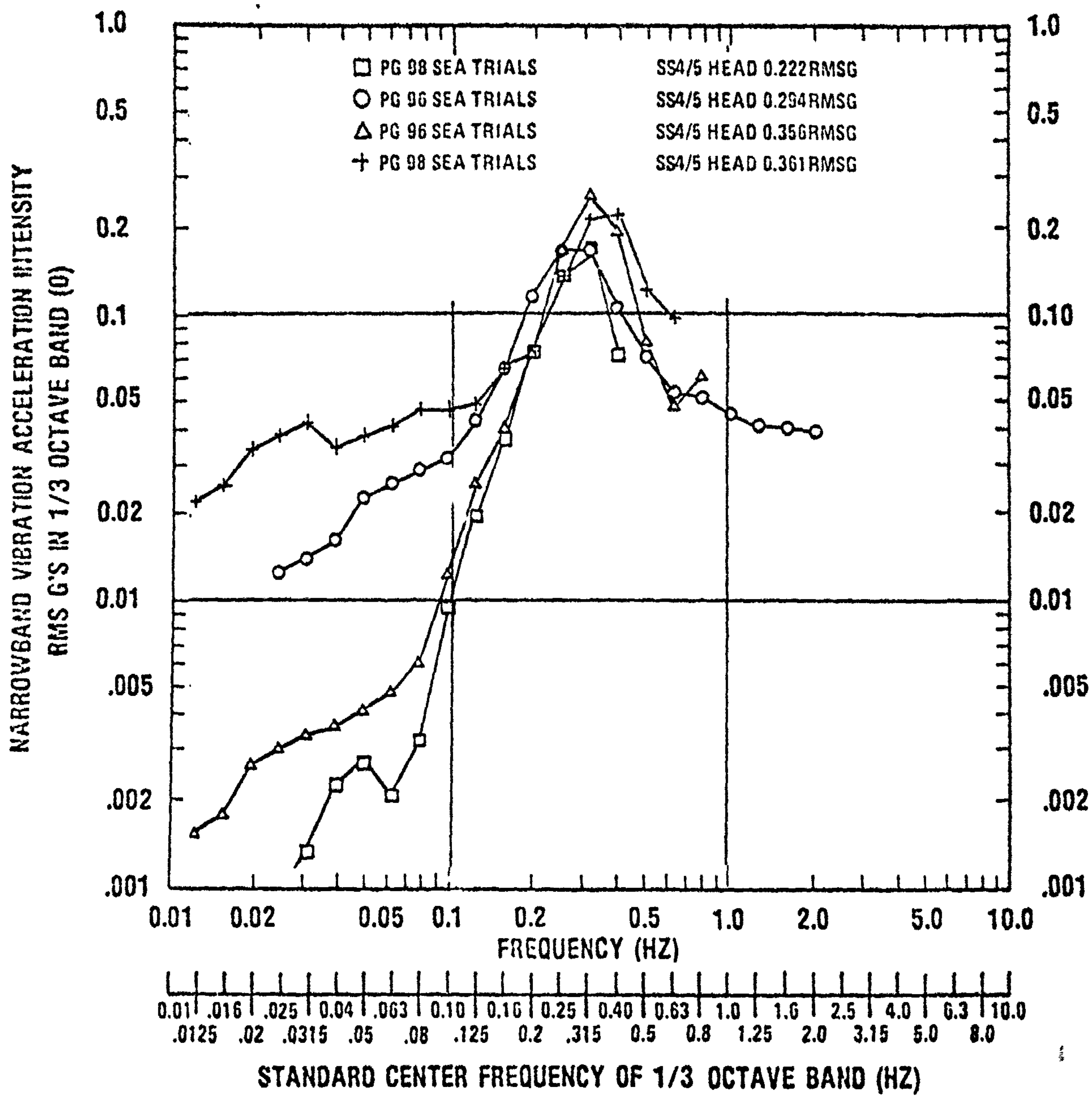

Figure A-8. Measured Motion Spectra for a PG-92 Class Patrol Gun Boat.

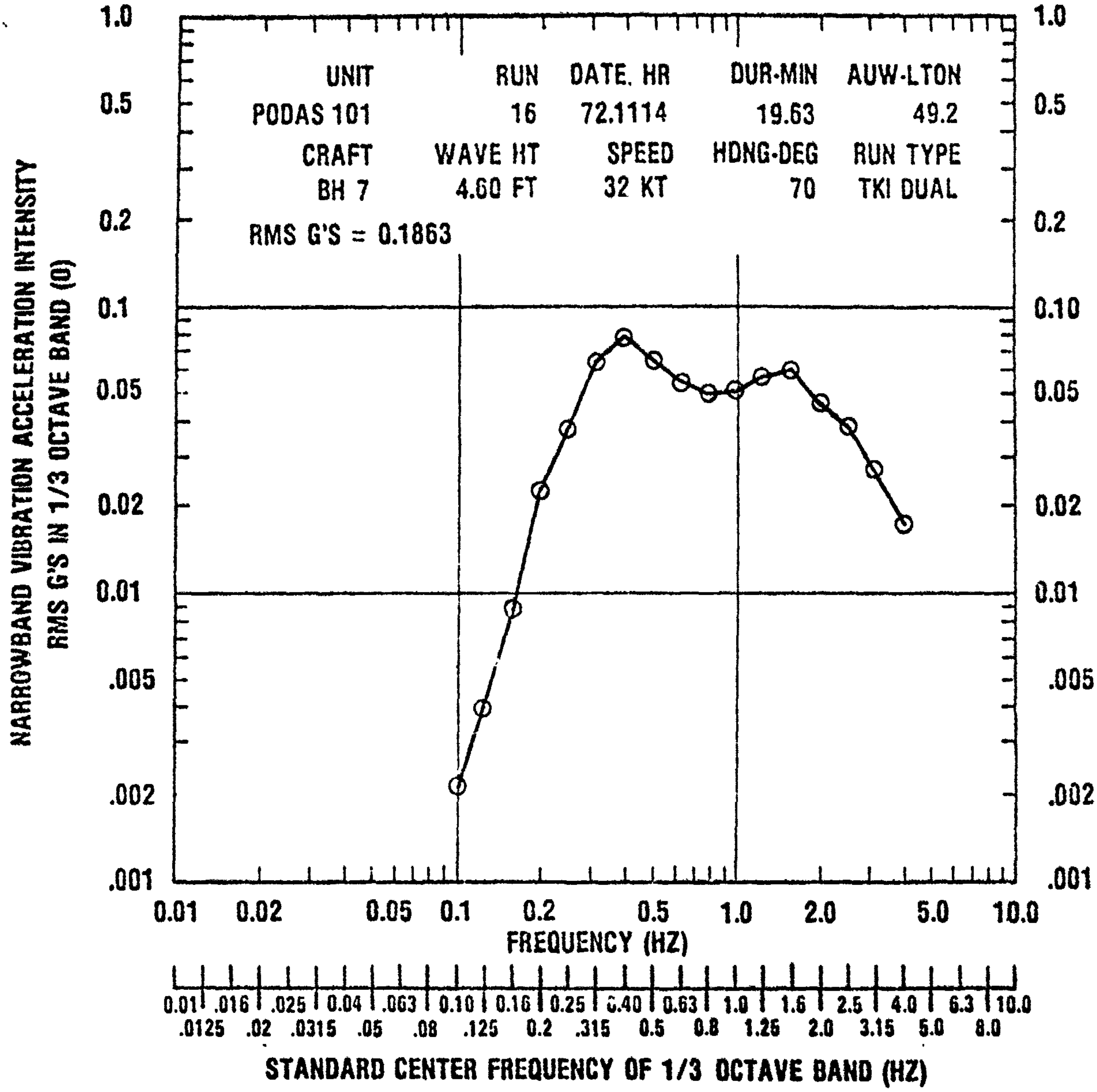

Figure A-9. Measured Motion Spectra for British Hovercraft BH-7.

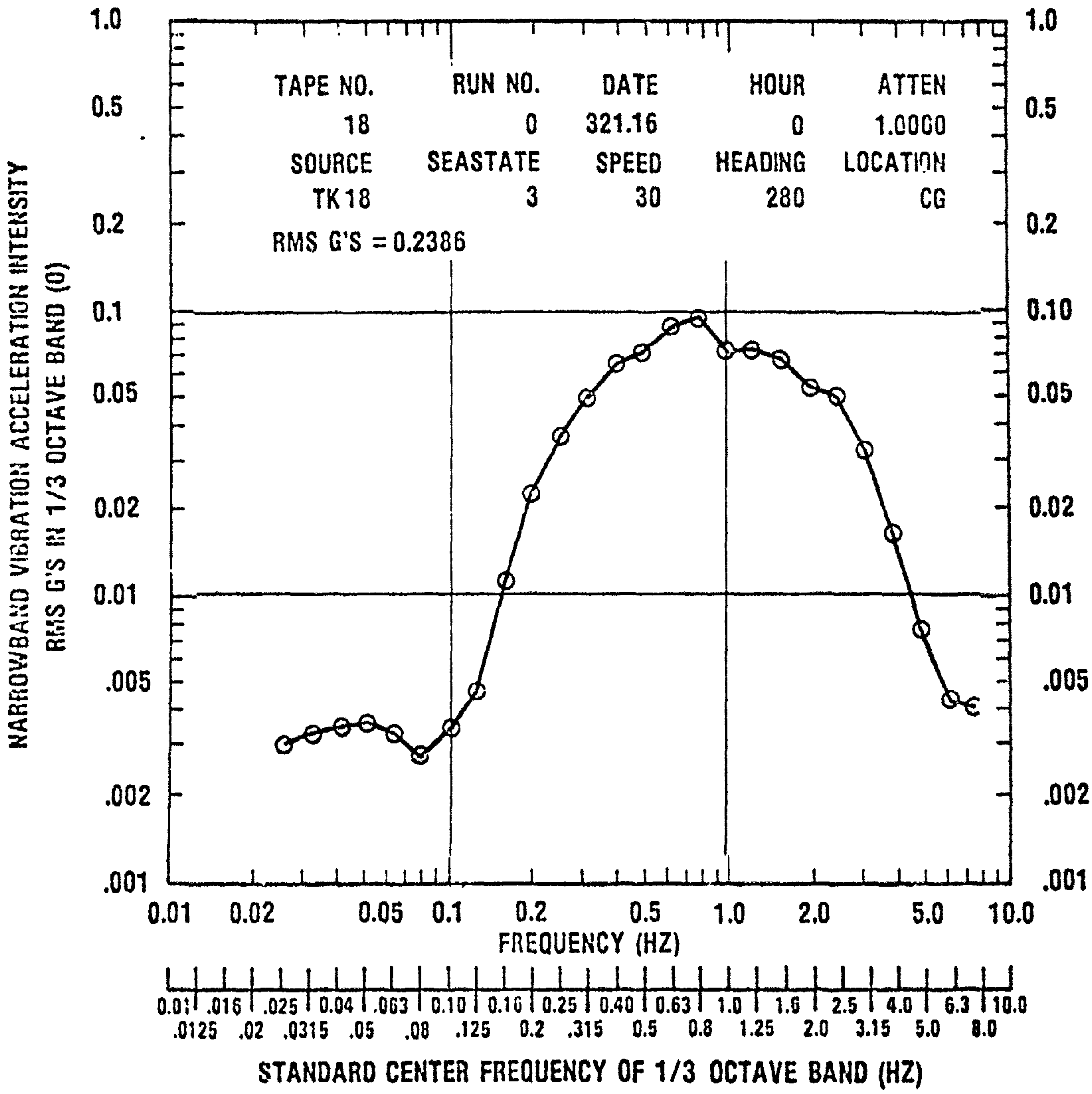

Figure A-10. Measured Motion Spectra for the SES-100B Test Craft.

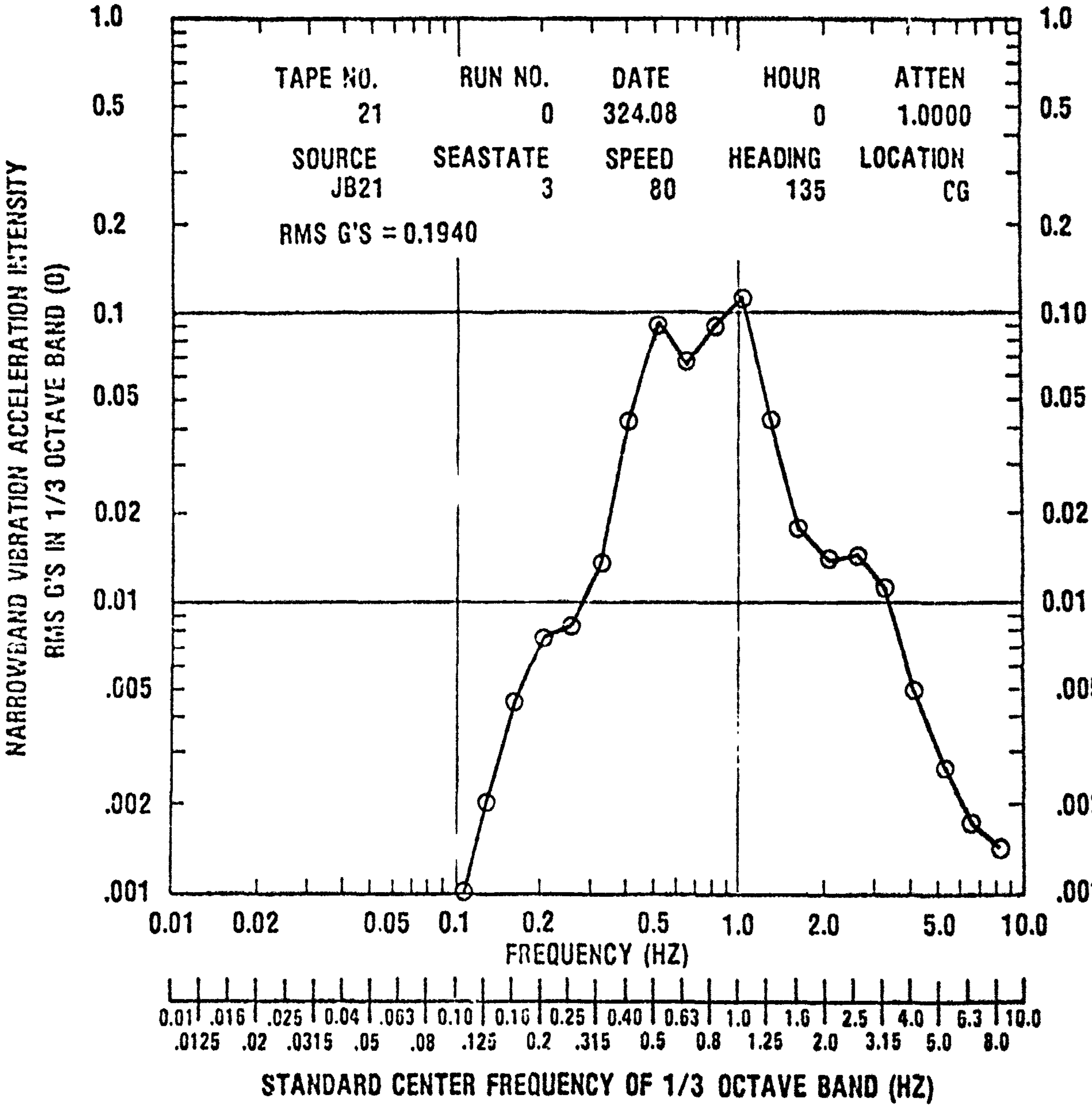

Figure A-11. Simulated Motion Data for a 2000-Ton SES Mathematical Model (Without Ride Control).

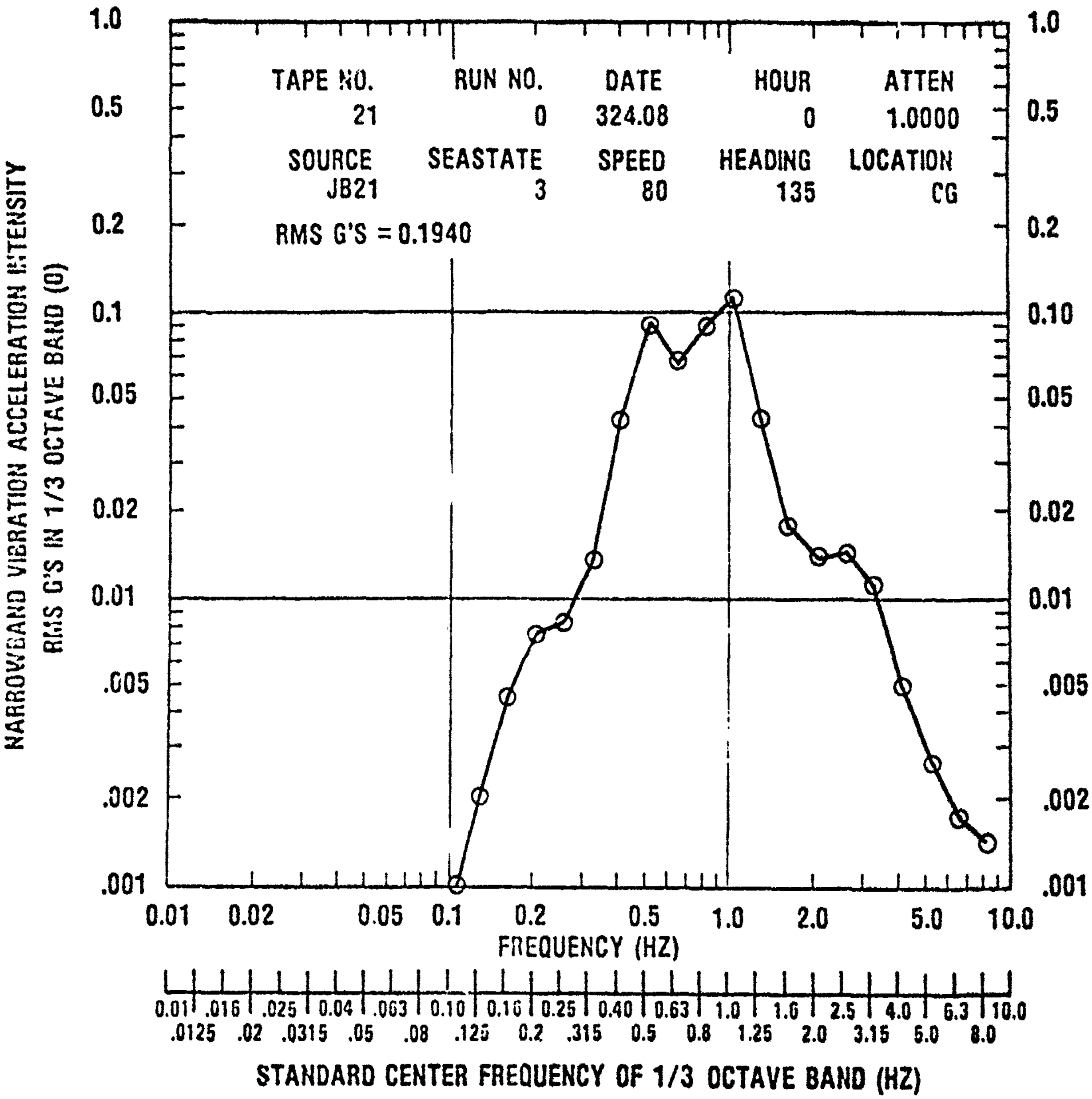

Figure A-11. Simulated Motion Data for a 2000-Ton SES Mathematical Model (Without Ride Control).

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